Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Gap Waveguides and PMC packaging: Octave Bandwidth mm- and submm-Wave Applications of Soft & Hard Surfaces, EBGs and AMCs

By

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Per-Simon Kildal (per-simon@kildal.se) (IEEE M'76–SM'81–F'95) is professor in antennas at Chalmers University of Technology in Gothenburg, Sweden since 1989. He is heading the Antenna group. His main tasks are to lead and supervise research within antenna systems. Until now, 22 persons have received a Ph.D. from him. Kildal received himself two doctoral degrees from the Norwegian Institute of Technology in Trondheim.

Kildal has authored more than 150 articles in scientific journals; concerning antenna theory, analysis, design and measurements. Two articles were awarded best paper awards by IEEE (1985 R.W.P. King Award and 1991 Schelkunoff Prize Paper Award). In 2011 he received the prestigious Distinguished Achievements Award from the IEEE Antennas and Propagation Society. It is their highest award.

Kildal has done the electrical design of the 40m x 120m cylindrical reflector antenna and line feed for the EISCAT scientific organization, and the dual-reflector Gregorian feed of the 300 m Ø radio telescope in Arecibo for Cornell University. He is the inventor behind technologies such as the dipole with beam forming ring, the hat antenna, and the eleven feed. All these feeds have been used in industry, and until now more than 1 million hat-fed reflectors have been manufactured for use in radio links. Kildal was the first to introduce the

reverberation chamber as an accurate measurement instrument for Over-The-Air (OTA) characterization of small antennas and wireless terminals for use in multipath environments with fading. Kildal is also the originator of the concept of soft and hard surfaces from 1988, today being regarded as the first metamaterials concept. This concept is the basis of his newest and most fundamental invention, the gap waveguide technology. His research is innovative and industrially oriented, and has resulted in several patents and related spinoff companies, the most known being Bluetest AB.

Kildal organizes and lectures in courses within the *European School of Antenna*. His textbook *Foundations of Antennas - A Unified Approach for Line-of-Sight and Multipath*, Kildal Antenn AB, 2015, is available for free at http://www.kildal.se as together with supporting slides and MATLAB handbook.

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CHALMERS

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Metasurfing for industrial applications since 1988

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Slide presentation published in the Forum of web based FERMAT Journal edited by R. Mittra, Aug. 2015

Introductory text

- I defined “soft and hard surfaces” in 1988. These were a generalization of the corrugated surfaces. Today we represent them ideally as **canonical** PEC/PMC strip grids, realized as **metasurfaces**.
- The simple and conceptual generalization made it easier to see new applications, and these came in terms of inventions. The patented hat antenna with a corrugated “soft” brim has been as a feed in a reflector antenna manufactured in more than 1 million copies for use in radio links.
- The soft surface is anisotropic, but has otherwise the same characteristics as an EBG surface. It stops waves from propagating along the surface. Thus, it is a forerunner of the EBG surface.
- I used the hard surface to make struts invisible in 1988 (i.e. to reduce forward scattering, also referred to as superstealth). The journal article was published in 1996, ten years before the first cloaking paper appeared. Thus, the hard struts was really the first cloaking concept, and they worked in practice over 20% bandwidth, for any polarization of an incident wave with given angle of arrival.
- The soft and hard surfaces have been used in many antenna applications and realized in many ways since 1988.
- This conceptual thinking resulted in the definition of gap waveguides in 2009. Gap waveguides are waveguides realized in a narrow air gap between parallel plates, by using a texture in one of the plates. The wave propagation is controlled by designing a stopband for normal parallel-plate modes, and allowing the waves to propagate along ridges, grooves or microstrips. This gives ridge, groove and microstrip gap waveguides.
- The stopband appears ideally those places where one of the surfaces is a PEC and the other a PMC. The gap between a PEC and a PMC cannot support any waves when it is narrower than quarter of the wavelength.
- We have since 2009 researched the gap waveguide to a competitive waveguide technology for wideband millimeterwave applications, including low loss transmission lines, high-Q filters, transitions, resonance-free EM packaging of microstrip and co-planar waveguide circuits and MMICs, distribution networks and directive antennas. The industrial applications are approaching.
- The present slides give an introduction to these concepts.
- Some selected references are given at the end.
- Many more references on gap waveguides can be found in the following book chapter:
  - A. Uz Zaman, P.-S. Kildal, “Gap Waveguides”, to appear in *Handbook of Antenna Technologies*, Springer 2016.
- The soft and hard surfaces and gap waveguides are lectured in the course on “Metasurfaces for Antennas” organized by European School of Antennas every third year. The next appearance is 5-9 October 2015 in Zagreb.

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Content

- Introduction
- Definition of soft and hard surfaces 1988
- Soft surface and bandgaps since 1988
- Hard surface and cloaking in 1996
- Gap waveguides since 2009
- Gap waveguide antennas since 2012
- Wideband directive antennas at 60 GHz
- Summary and future
- Independent research by Erik Lier:
  Metamaterial-based horn-antennas based on soft and hard surfaces

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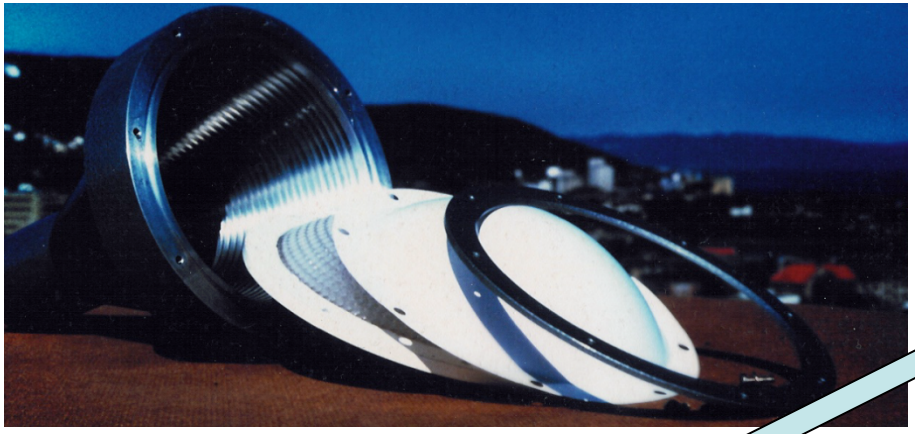
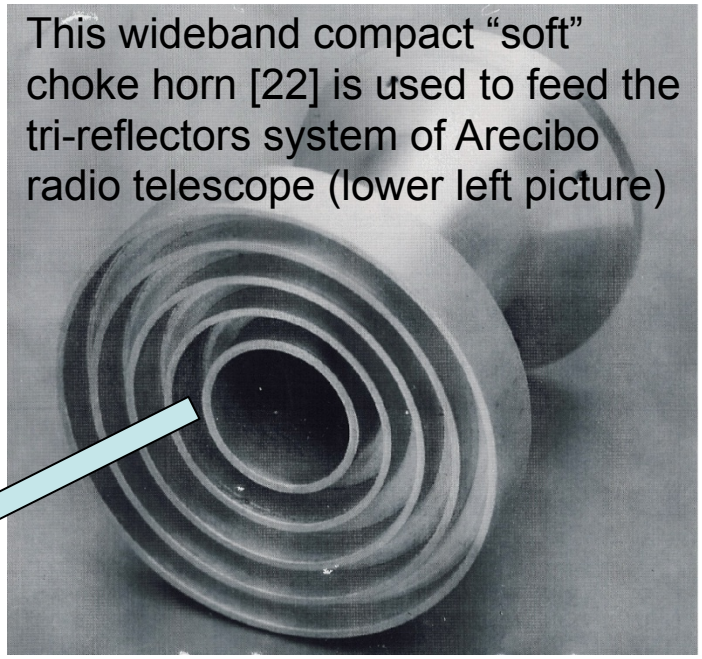
Research on corrugated horns for reflector antennas during 1982-1995 forms the basis of the generalisation to soft surfaces [1-2]

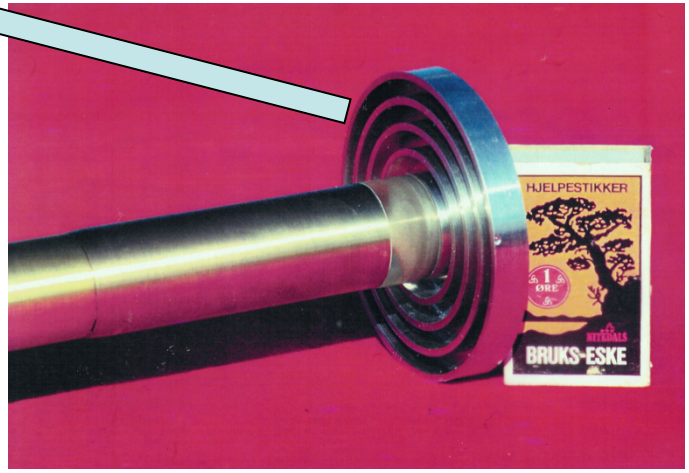




The 1st result of this generalization was the corrugated "soft-brimmed" hat feed in ring-focus paraboloid, Kildal 1987 [17-20]

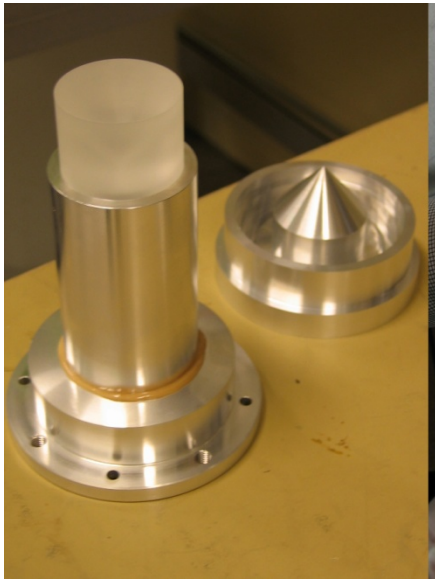
Thus, the concept of soft and hard surfaces helps improve engineering creativity. It is useful!

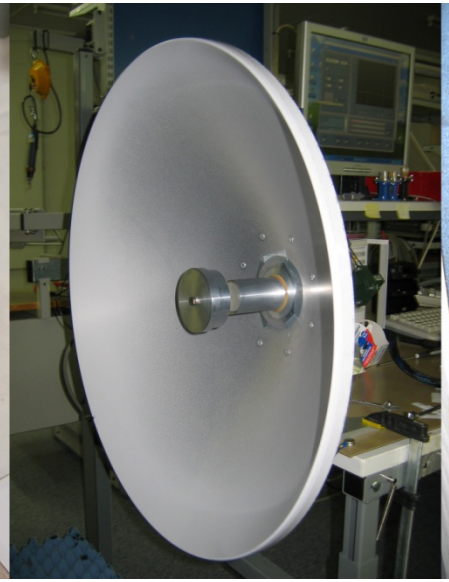
Low sidelobes
good efficiency due to
a soft surface [17-20]



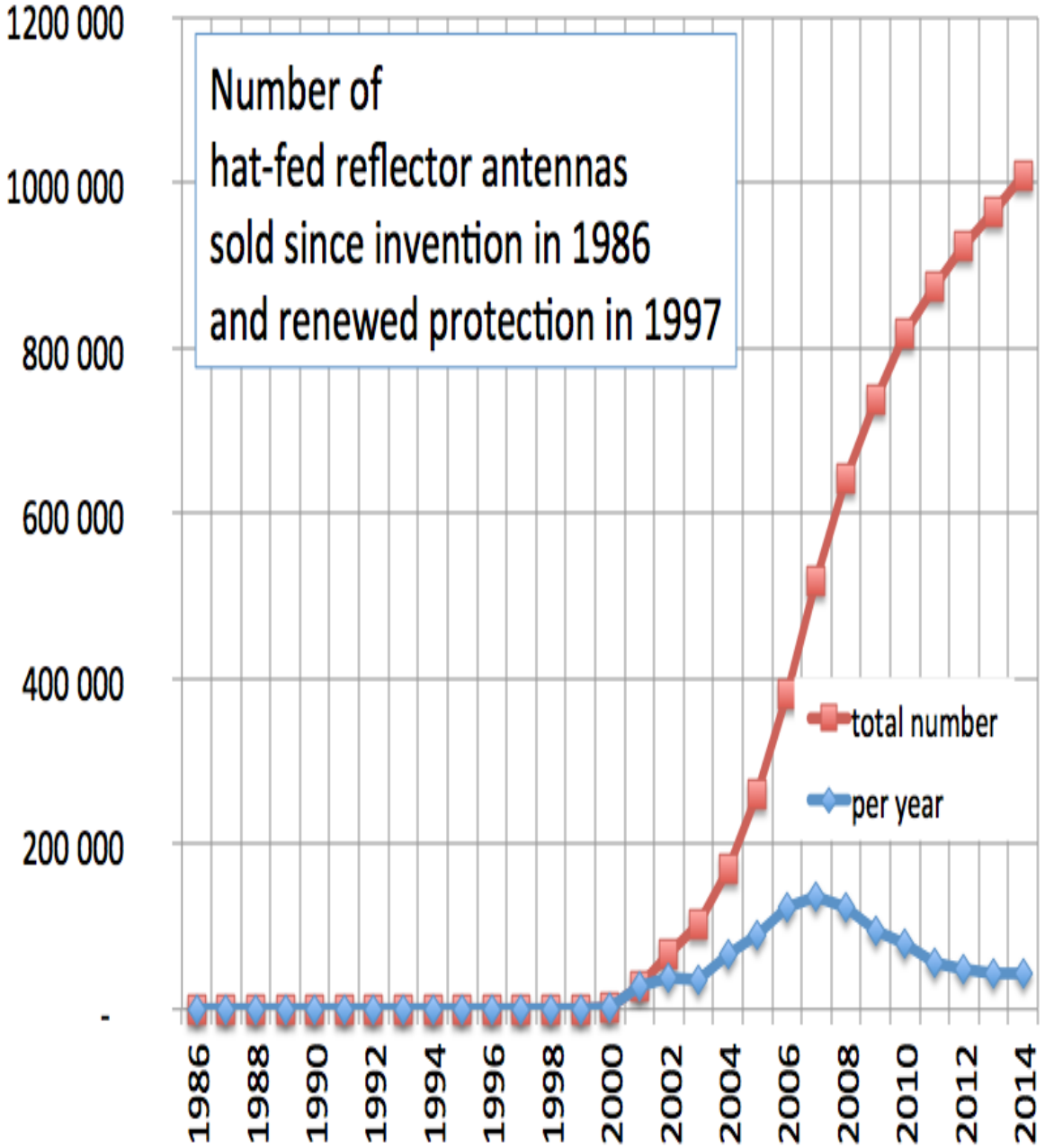
Hat-fed reflector antennas are still in production for radio links

The below photos are from an improvement done in 2006 [20].





Number of produced comhat antennas for Ericsson´s MINILINK till now



The EM concept of soft and hard surfaces dates back to 1988 [1-2] (Kildal) and regained interest in 1999 (Sievenpiper) [24]

DEFINITION OF ARTIFICIALLY SOFT AND HARD SURFACES FOR ELECTROMAGNETIC WAVES

Indexing terms: Antennas, Antenna theory, Electromagnetic field theory, EM waves

The widely used transversely corrugated surfaces and other alternative surfaces having the same anisotropic surface impedance deserve a common name. Here it is proposed to call them soft surfaces by analogy with the soft surfaces in acoustics. In the same way artificially hard surfaces are defined. Cylindrical hard waveguides of any cross-sectional shape can support TEM waves.

Introduction: Transversely corrugated surfaces have for more than 20 years been used to design hybrid-mode horn antennas with symmetrical radiation patterns and low cross-polarisation.[1–4] Recently, hybrid-mode horns have been realised also by other surfaces, that have the same anisotropic surface impedance as the corrugated surface.[5–8] Transversely corrugated surfaces have also been applied to the design of other types of antennas, e.g. the hat feed.[9] Surfaces like this that can be realised in several ways and can be applied to

ELECTRONICS LETTERS 4th February 1988 Vol. 24 No. 3

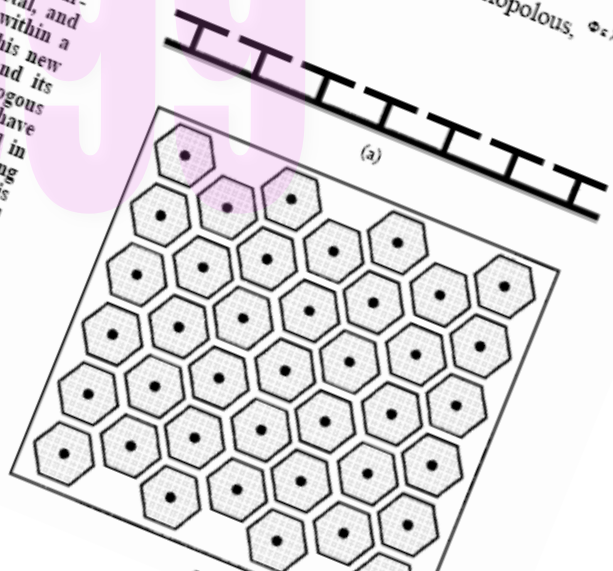
IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 47, NO. 11, NOVEMBER 1999

High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band

Dan Sievenpiper, Member, IEEE, Lijun Zhang, Romulo F. Jimenez Broas, Nicholas G. Alexópolous, Fellow, IEEE, and Eli Yablonovitch, Fellow, IEEE

A new type of metallic electromagnetic structure eloped that is characterized by having high sur- Although it is made of continuous metal, and nts, it does not conduct ac currents within a band. Unlike normal conductors, this new port propagating surface waves, and its hase reversed. The geometry is analogous rface in which the corrugations have -circuit elements, and distributed in e surface can be described using even though the periodicity is elength. This unique material agnetic problems, including

surfaces, photonic textured surfaces.



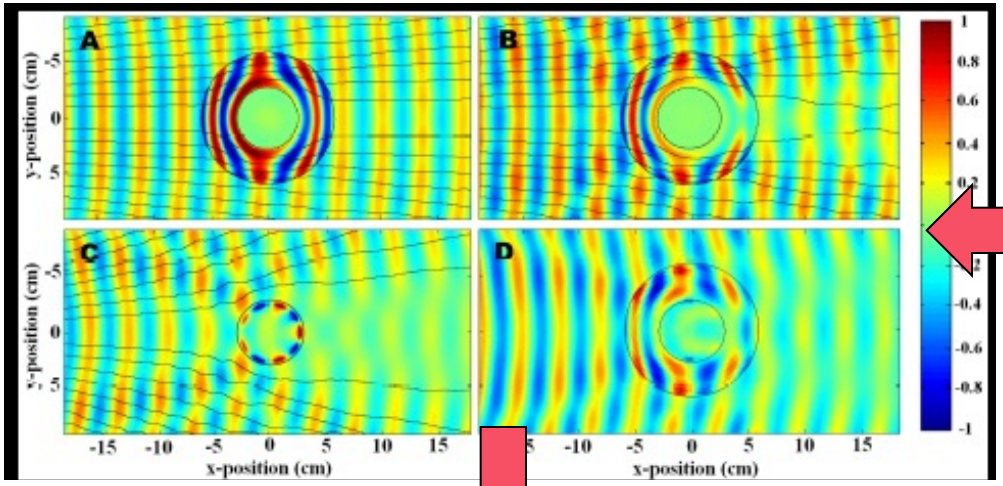
2005: The relation between EBG surfaces and soft&hard surfaces was explained in a table in a Special Issue of IEEE Transactions on Antennas and Propagation [5]. All are metasurfaces.

Canonical Surface		E-field Polarization	
		VER or TM	HOR or TE
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT →	STOP	STOP
	HARD →	GO	GO
PMC-type EBG	grazing ↗	STOP	STOP
	close to normal	PMC	

Table will be explained later!

Explanations of Abbreviations

- GO surfaces: Enhances propagation of waves along surface
- STOP surface: Stops propagation of waves along surface
- PEC = Perfect Electric Conductor
- PMC = Perfect Magnetic Conductor
- AMC = Artificial Magnetic Conductor
- PBG = Photonic Bandgap Material
- EBG = Electromagnetic Bandgap Material
- EMXtals = Electromagnetic Crystals



2006: Schurig, Pendry et al published a metamaterials graded index cloak in Sciencexpress.

Rated as the Fifth largest breakthrough in science in 2006.

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Scientists may be able to make magic like Harry Potter

Thursday, May 25, 2006; Posted: 4:59 p.m. EDT (20:59 GMT)

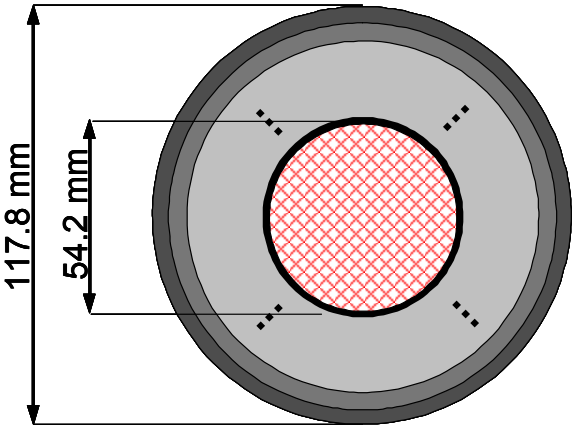
WASHINGTON (AP) -- Imagine an invisibility cloak that works just like the one Harry Potter inherited from his father.

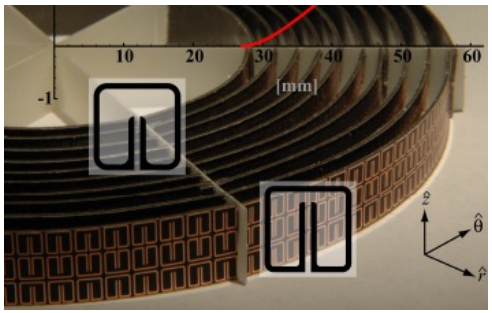
Researchers in England and the United States think they know how to do that. They are laying out the blueprint and calling for help in developing the exotic materials needed to build a cloak.

The keys are special manmade materials, unlike any in nature or the Hogwarts School of Witchcraft and Wizardry. These materials are intended to steer light and other forms of electromagnetic radiation around an object, rendering it as invisible as something tucked into a hole in space.

Scientists theorize they could make a real life invisibility cloak like Harry Potter's.

Appeared in media all over the world after this CNN report.





The hard surface evolved naturally from the soft one [1-2].

1996: Kildal et al published the first journal article on how the hard surface can be used
to reduce blockage from feed support struts of reflector antennas [41],

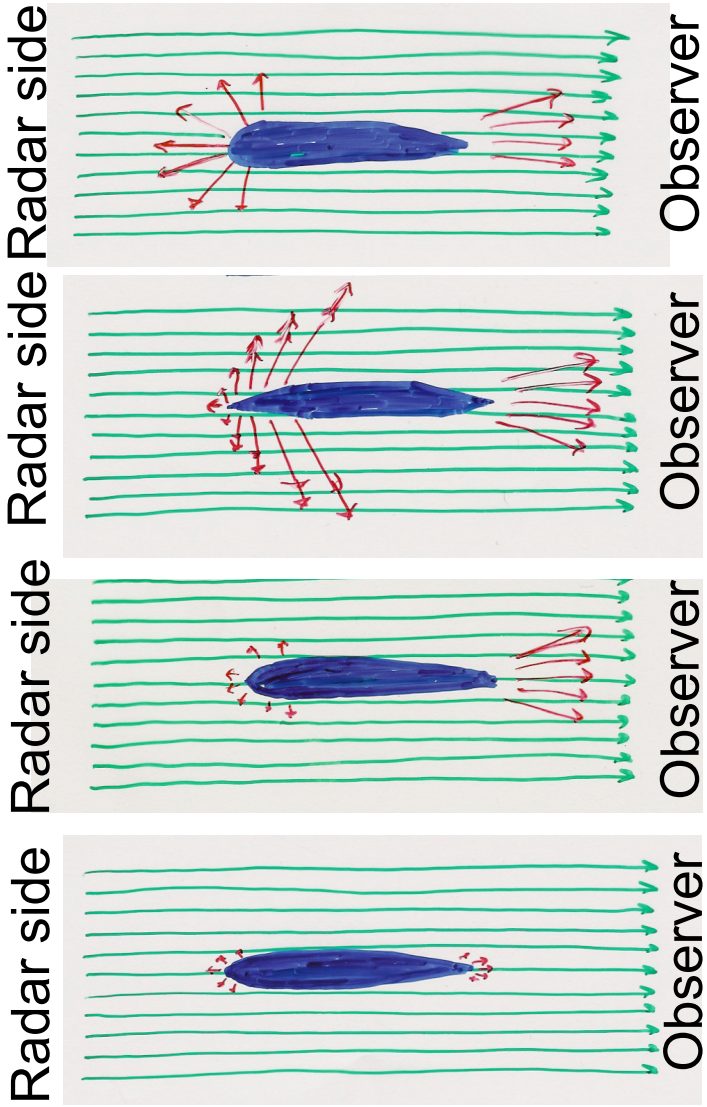
i.e. to make them invisible, nowadays called cloaking.

There were several conference papers during the years before [39-40].

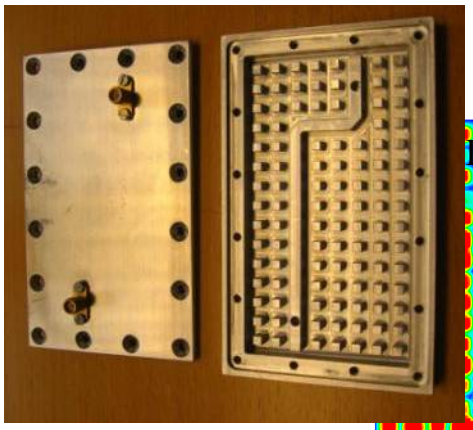
The hard surface gave birth to the idea of superstealth [3] which clearly is the same as cloaking.

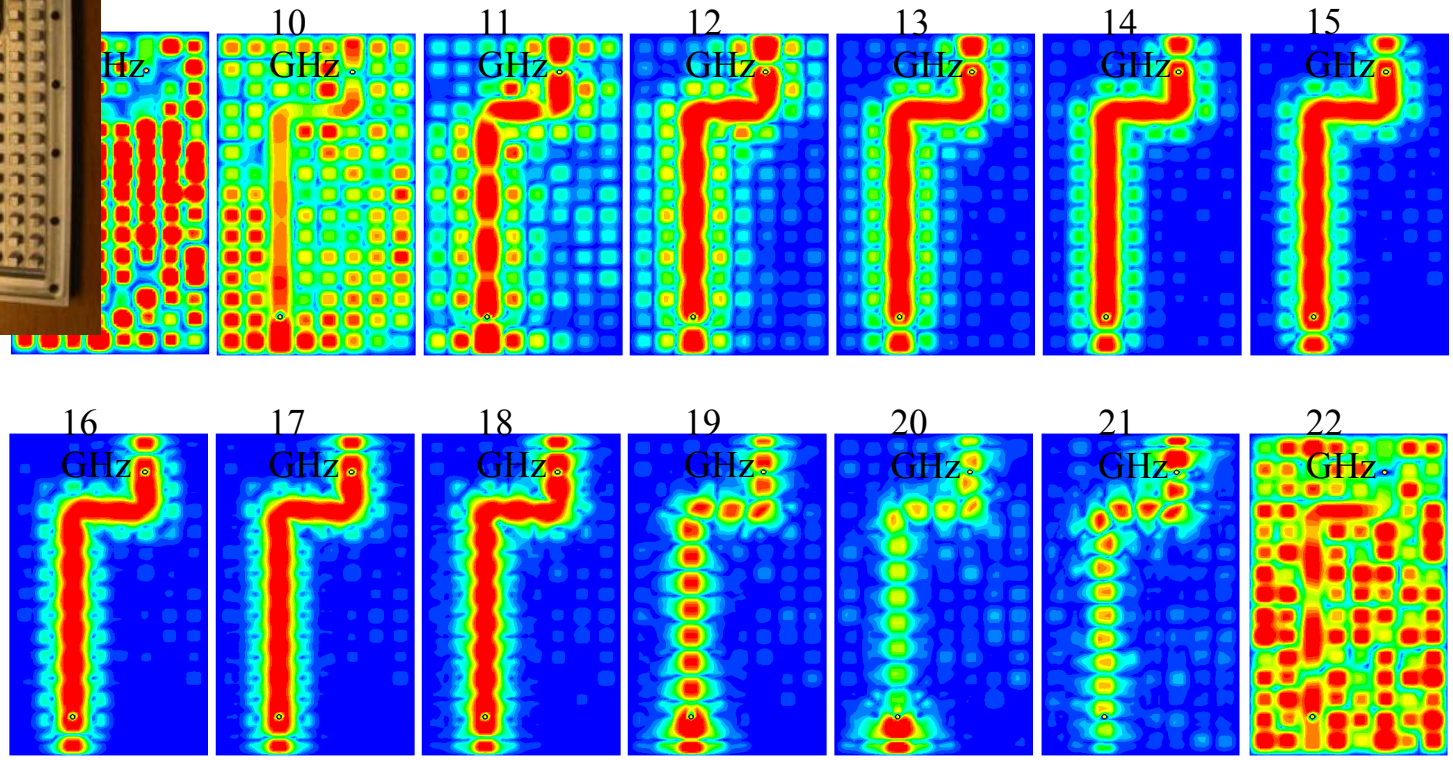
These illustrations of superstealth technology
are from presentation at Nordic conference Antenna 94 [3]

- Object subject to radar waves (green rays), and the backwards reflected and forward scattered waves (red rays).
- Common stealth technology directs reflected rays (red) away from radar.
- Radar absorbing material removes reflected rays.
- Superstealth technology leaves the object invisible also to observers on the opposite side of the object, i.e. the waves flow around the object and removes the appearance of it. This can be realized with a so-called hard surface, for small objects..

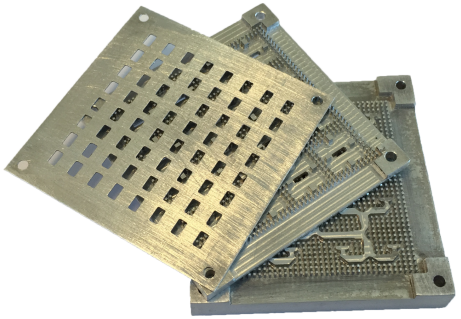


The gap waveguide was invented in 2008 [44-46]





Now in 2015 we make high-Q filters [61], and directive planar antennas at 60 GHz [60] → → and we package MMICs [64]



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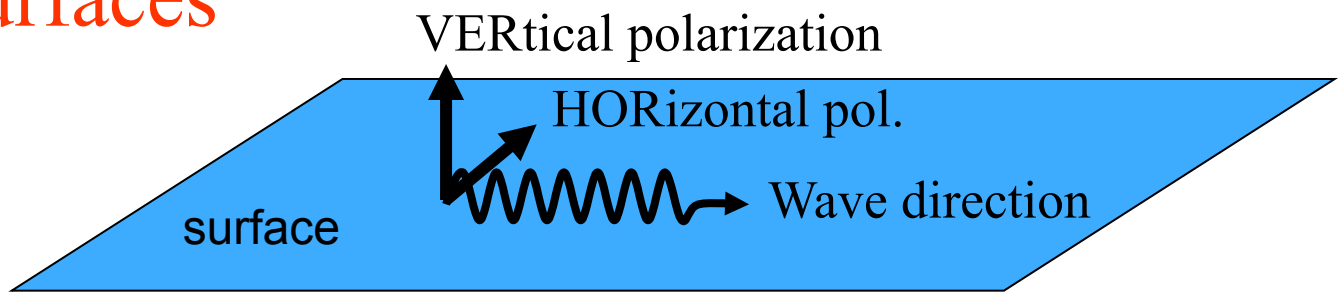
The term "Soft and hard surfaces" originates from boundary conditions used in acoustics and diffraction theory [1-2]

p is acoustic pressure in table below

Surface	Boundary condition	Can waves propagate at surface?
Soft	$p = 0$	No
Hard	$\frac{\partial p}{\partial n} = 0$	Yes

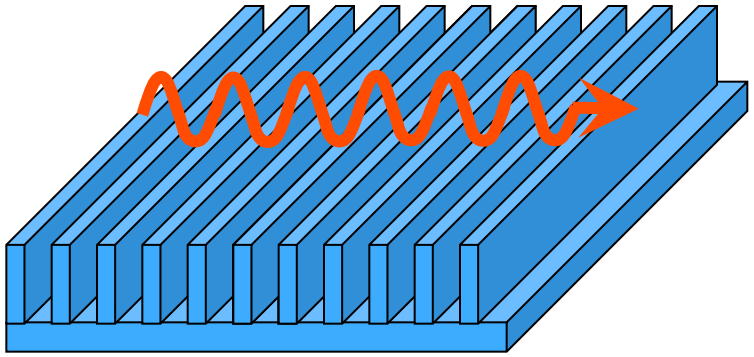
We wanted polarization-independent artificially soft and hard surfaces for antennas



Type of surface	Boundary condition	Wave propagation at surface?	Dual-polarized systems
Smooth conductor	$E_{HOR} = 0$ $\partial E_{VER}/\partial n = 0$	**No: STOP for HOR pol.** **Yes: GO for VER pol.**	**Never wanted**
Soft surface	$E_{HOR} = 0$ $E_{VER} = 0$	**No: STOP for HOR pol.** **No: STOP for VER pol.**	**Sometimes wanted**
Hard surface	$\partial E_{HOR}/\partial n = 0$ $\partial E_{VER}/\partial n = 0$	**Yes: GO for HOR pol.** **Yes: GO for VER pol.**	**Sometimes wanted**

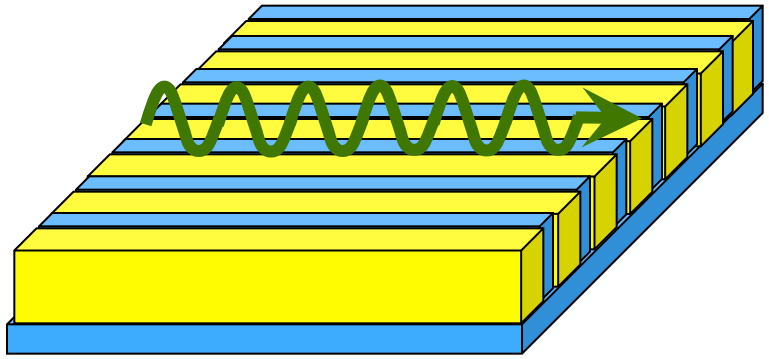
Realization of soft and hard surfaces with corrugations [1-2]

Soft STOP surface (left)



Transverse air-filled corrugations

Hard GO surface (right)



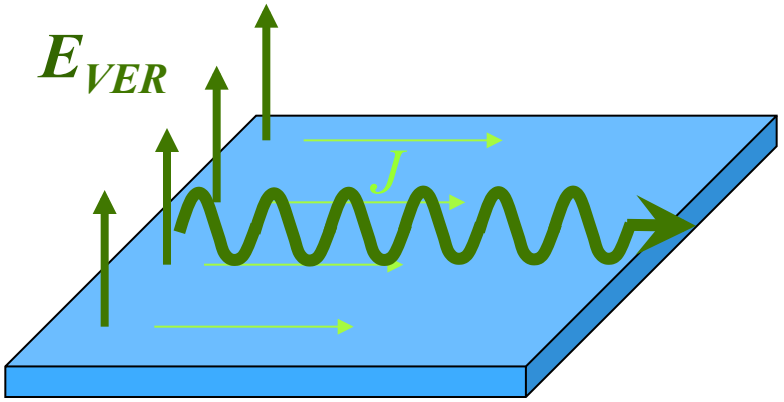
Longitudinal dielectric-filled corrugations

PEC: Wave propagation along surface

VER propagation GOes with

$$\partial E_{VER} / \partial n = 0$$

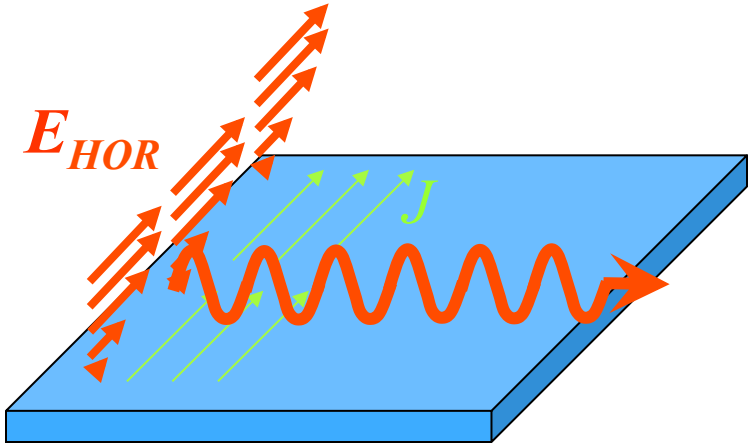
at surface.



HOR polarization STOPs with

$$E_{HOR} = 0$$

at surface

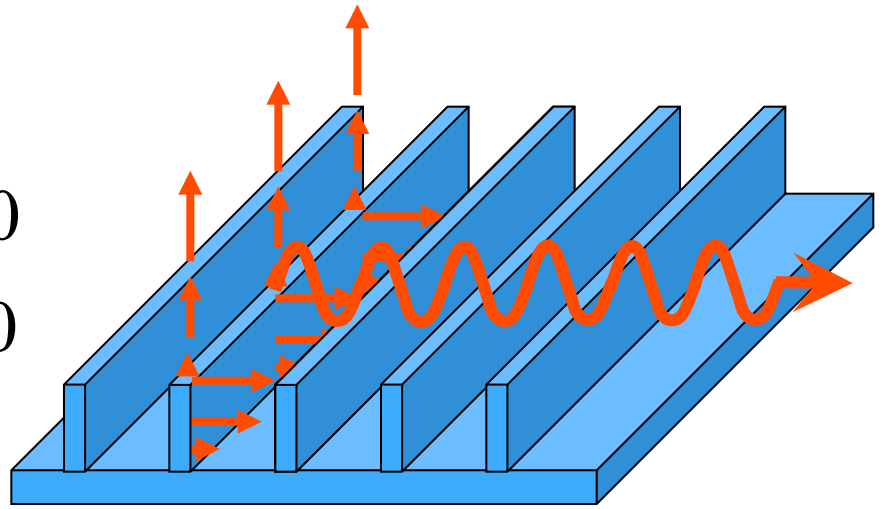


Soft surface: Principle of operation for transverse corrugations (current fences)

E_{VER} sees PMC (transformation from short-circuit to open-circuit in grooves)

$$E_{VER} = 0$$

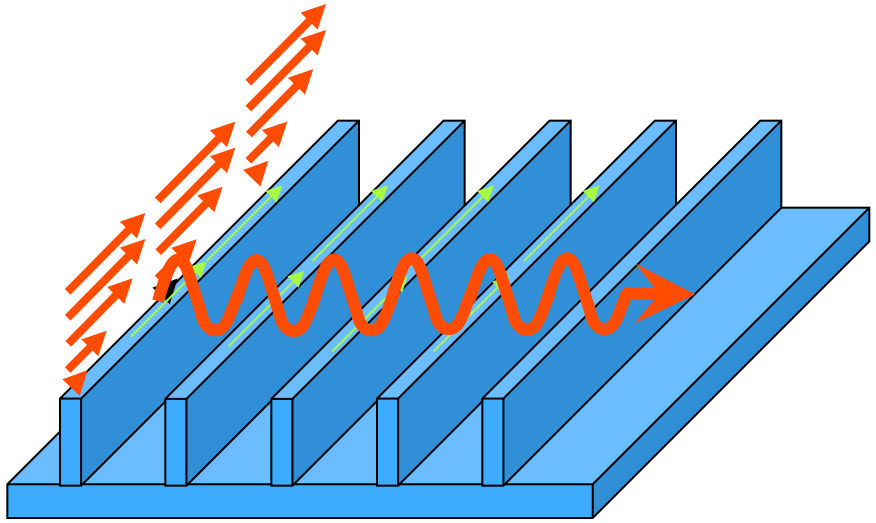
$$J_{long} = 0$$



E_{HOR} sees PEC ridges. No penetration into grooves.

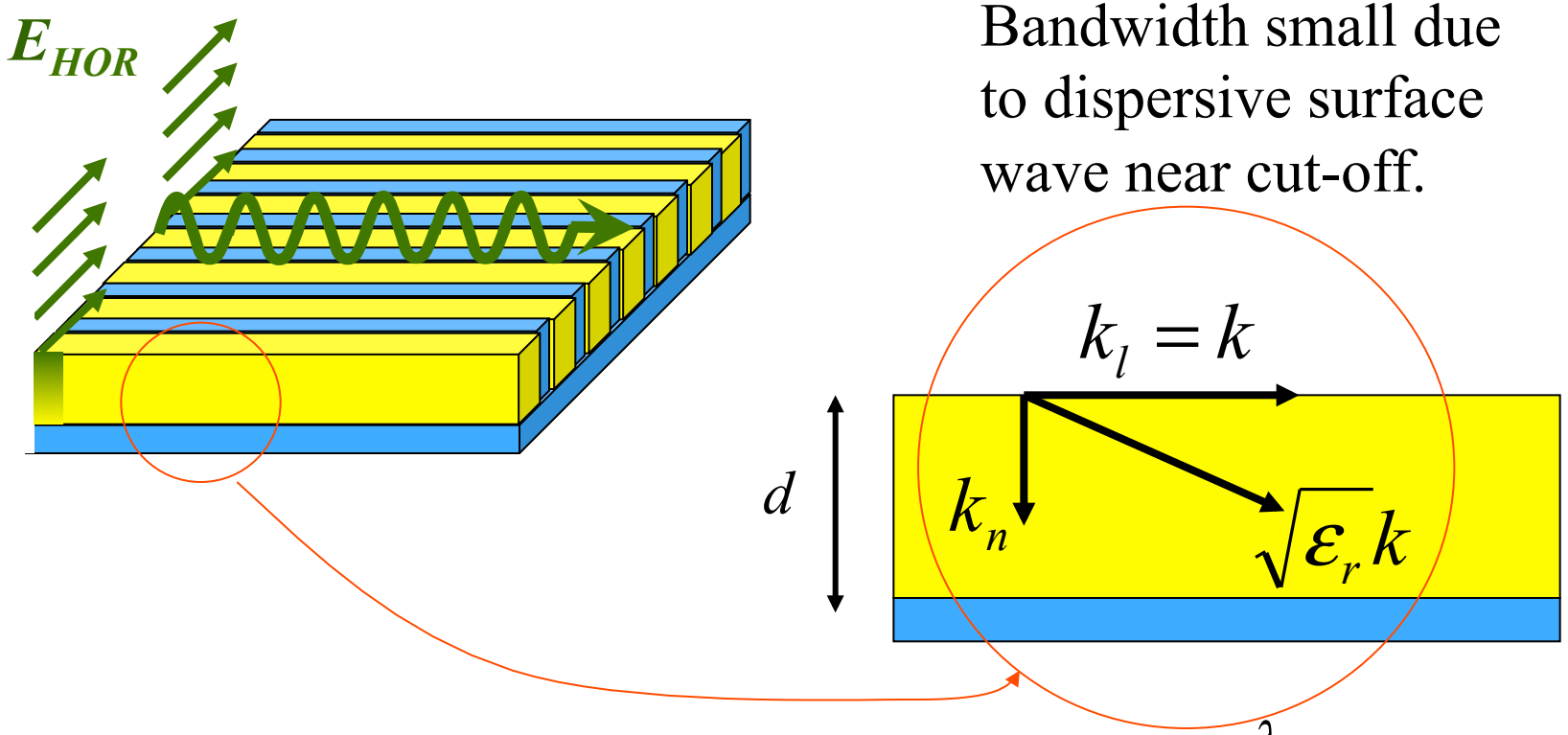
$$E_{HOR} = 0$$

$$J_{transv} = undesturbed$$



Hard surface: Principle of operations for longitudinal corrugations (current lanes)

We MUST for the hard case have dielectric filling in the corrugations to get the desired transformation from PEC to PMC

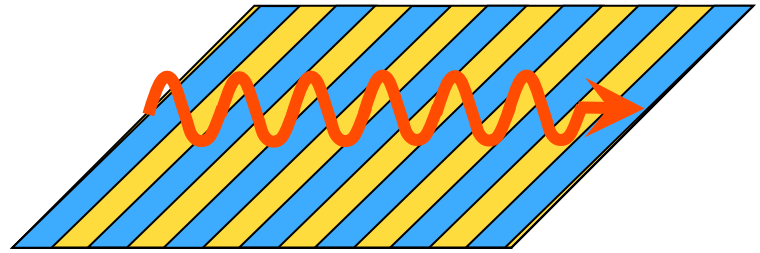


Bandwidth small due to dispersive surface wave near cut-off.

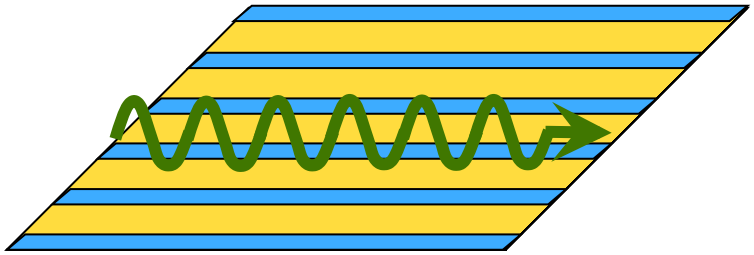
PMC (TEM frequency) if $k_n d = \pi/2 \;\Rightarrow\; d = \dfrac{\lambda}{4\sqrt{e_r - 1}}$

PEC/PMC strip model of ideal soft and hard surfaces (2005) [5]

- Ideal soft surface = **STOP** surface
- Ideal hard surface = **GO** surface



The strips become current fences

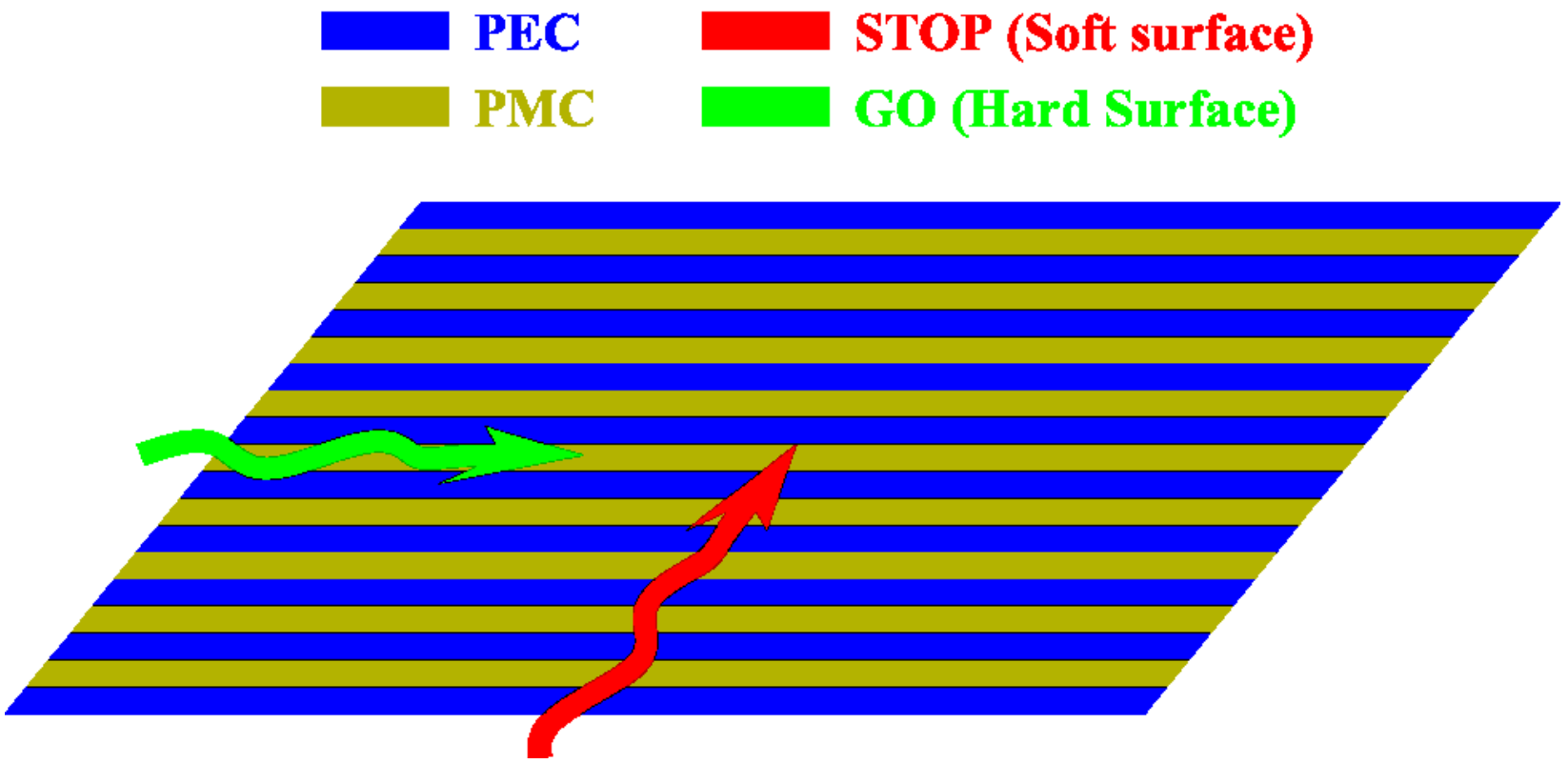


The strips become current lanes

$$strip\ \ period \rightarrow 0$$

Red wave symbol means propagating waves will STOP, green symbol means they will easily GO.

PEC/PMC strip surface can be either soft or hard, depending on plane of incidence



Comparison with respect to propagation of waves along the surface (surface waves) [5].

Note that the color coding explains what kind of surface it is.

Canonical Surface		E-field Polarization	
		VER or TM	HOR or TE
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT	STOP	STOP
	HARD	GO	GO
PMC-type EBG	grazing	STOP	STOP
	close to normal	PMC	

The EBG surface will be explained later!

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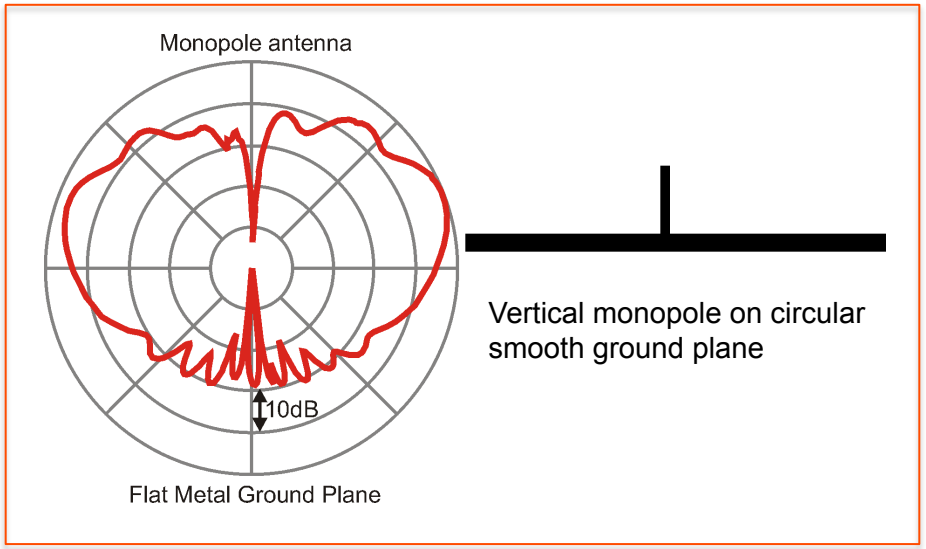
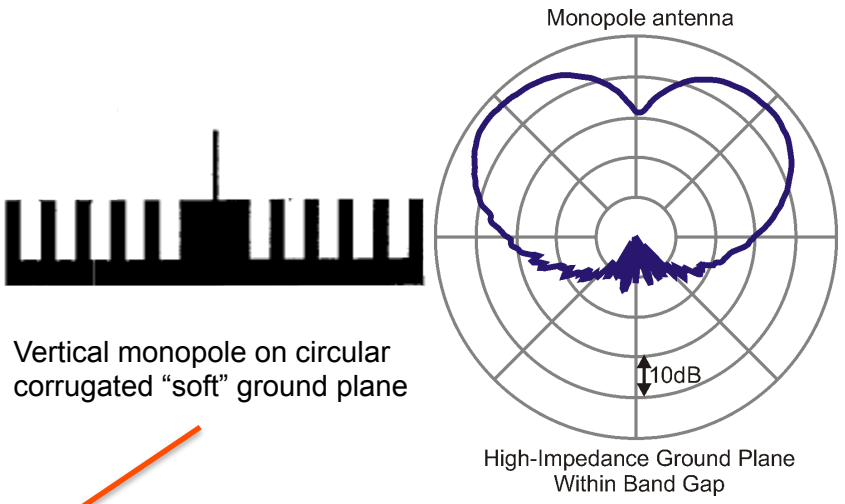
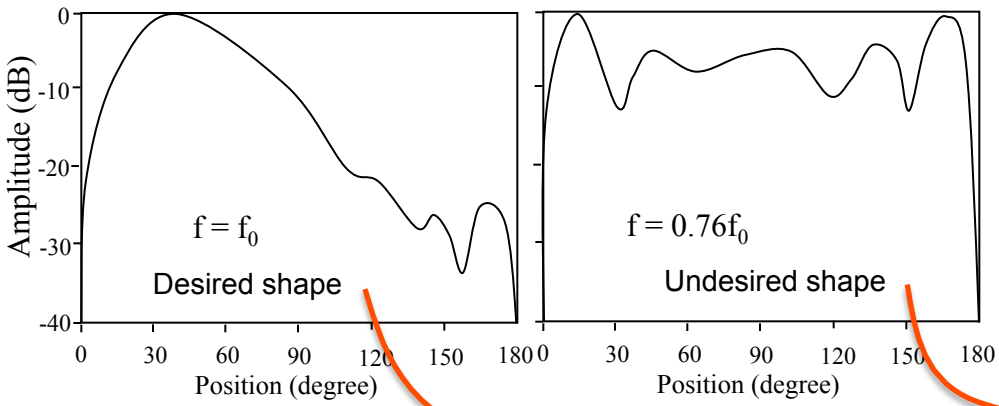
Soft surfaces were from the start characterized in terms of the engineering quantity bandwidth, of e.g. cross polarization or side lobes

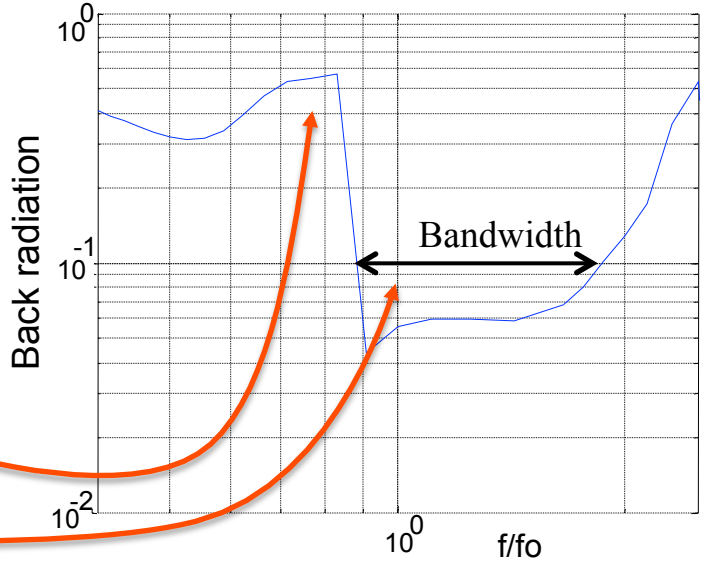




Bandwidth calculated from the shape of the radiation pattern



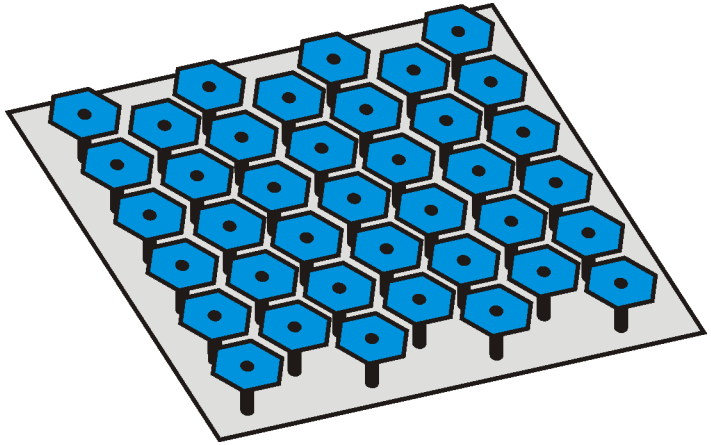
Bandwidth calculated from the back radiation efficiency

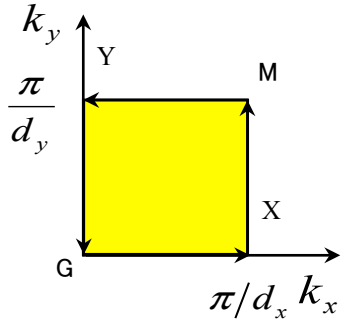


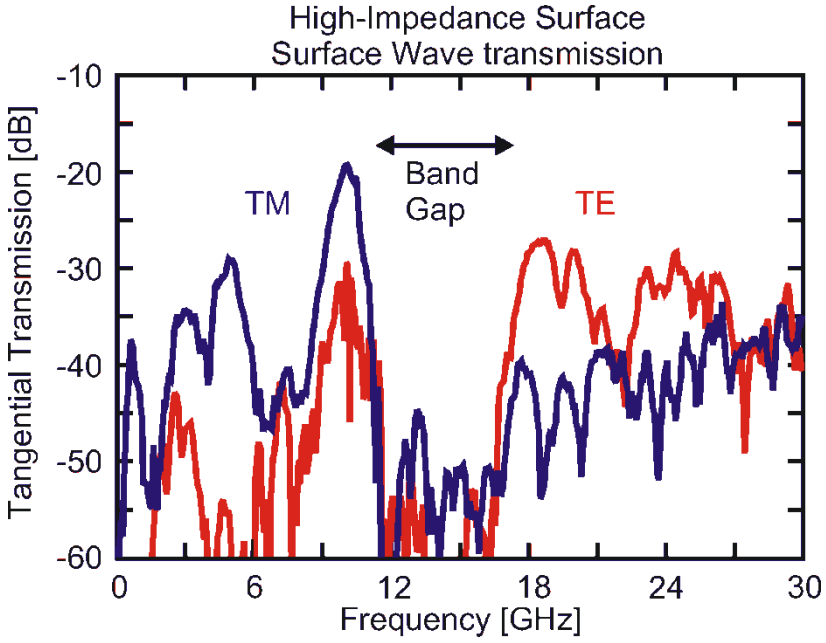
EBG surfaces were characterized from the dispersion diagram for the guided wave without knowing how this relates to an engineering bandwidth

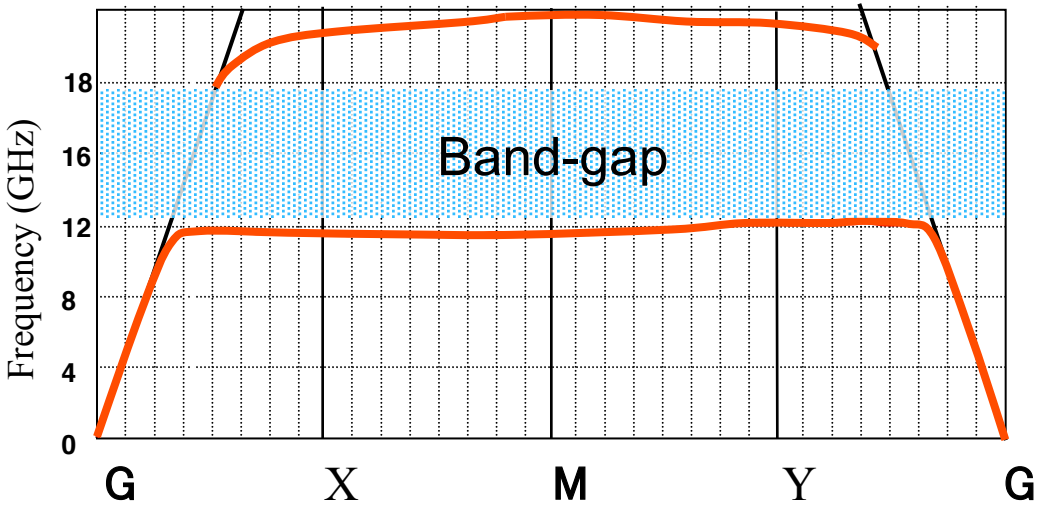
Sievenpiper 1999 [24]:
Mushroom surface
Forbidden frequency bands

Electromagnetic bandgap (EBG) surface









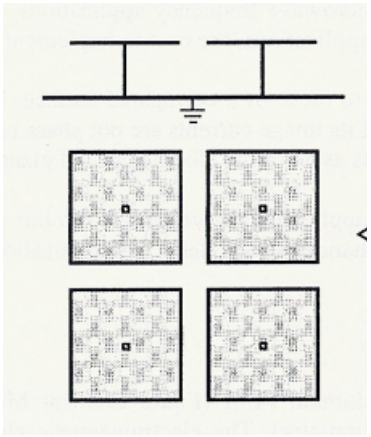
Comparison with respect to propagation of waves along the surface (surface waves) [5].

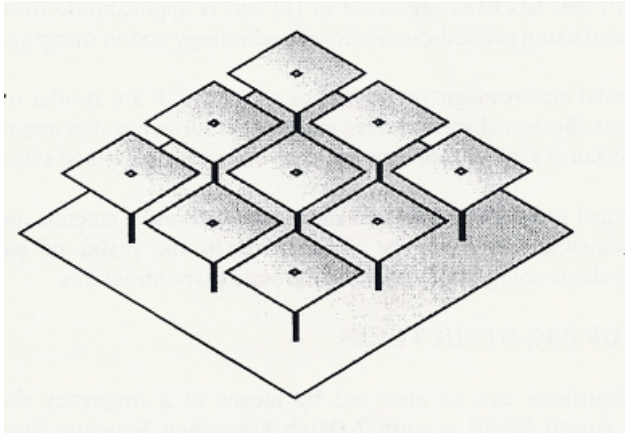
Canonical Surface		E-field Polarization	
		VER or TM	HOR or TE
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT	STOP	STOP
	HARD	GO	GO
PMC-type EBG	grazing	STOP	STOP
	close to normal	PMC	

The isotropic EBG surface has similar **STOP** performance as the anisotropic SOFT surfaces, for gracing incidence. The EBG is PMC only for non-gracing incidence. Thus, the PMC condition does NOT define its bandgap for TE-case, i.e. HOR polarization.

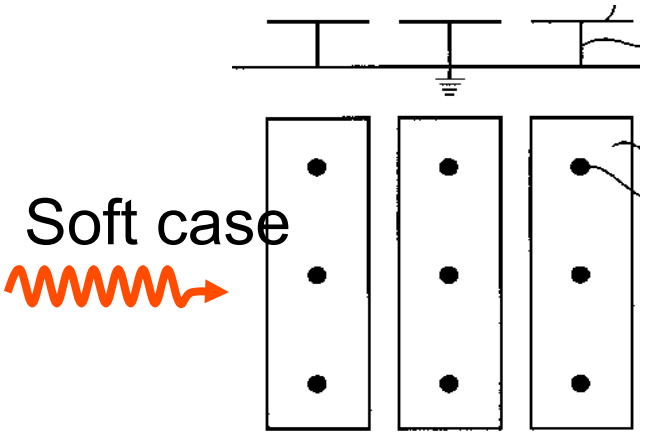
Sievenpiper's mushroom surfaces stimulated realization of strip-type soft and hard surfaces, and later other metamaterial realizations.

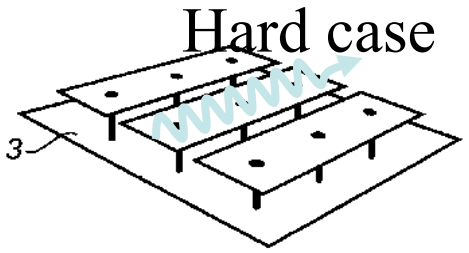
Original EBG:





Strip-type EBG or soft surface:





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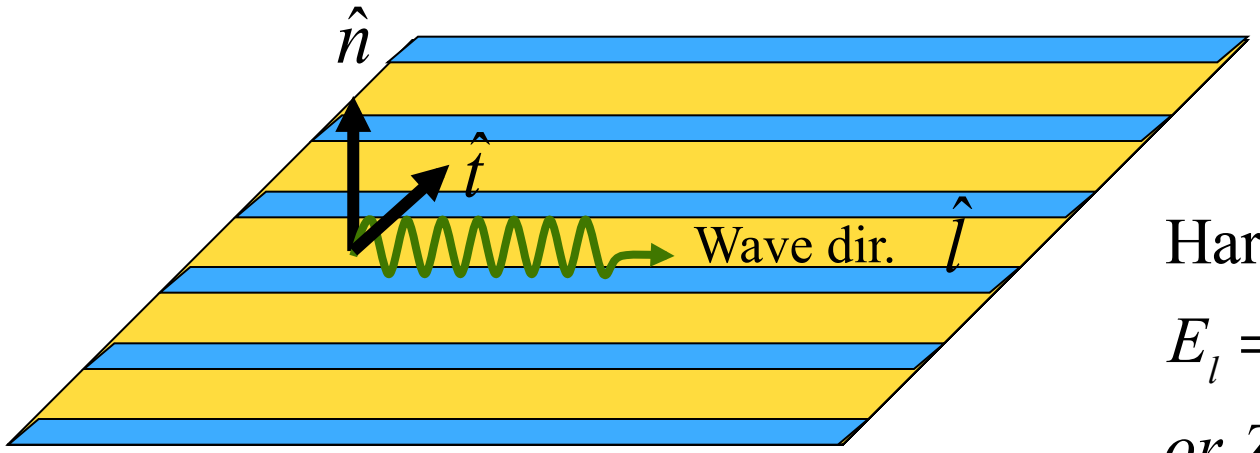
  Metamaterial-based horn-antennas based on soft and hard surfaces

Hard surface supports TEM wave intrinsically [2]



Hard surface defined by

$$E_l = H_l = 0$$

$$or\ Z_l = 0, Z_t = \infty$$

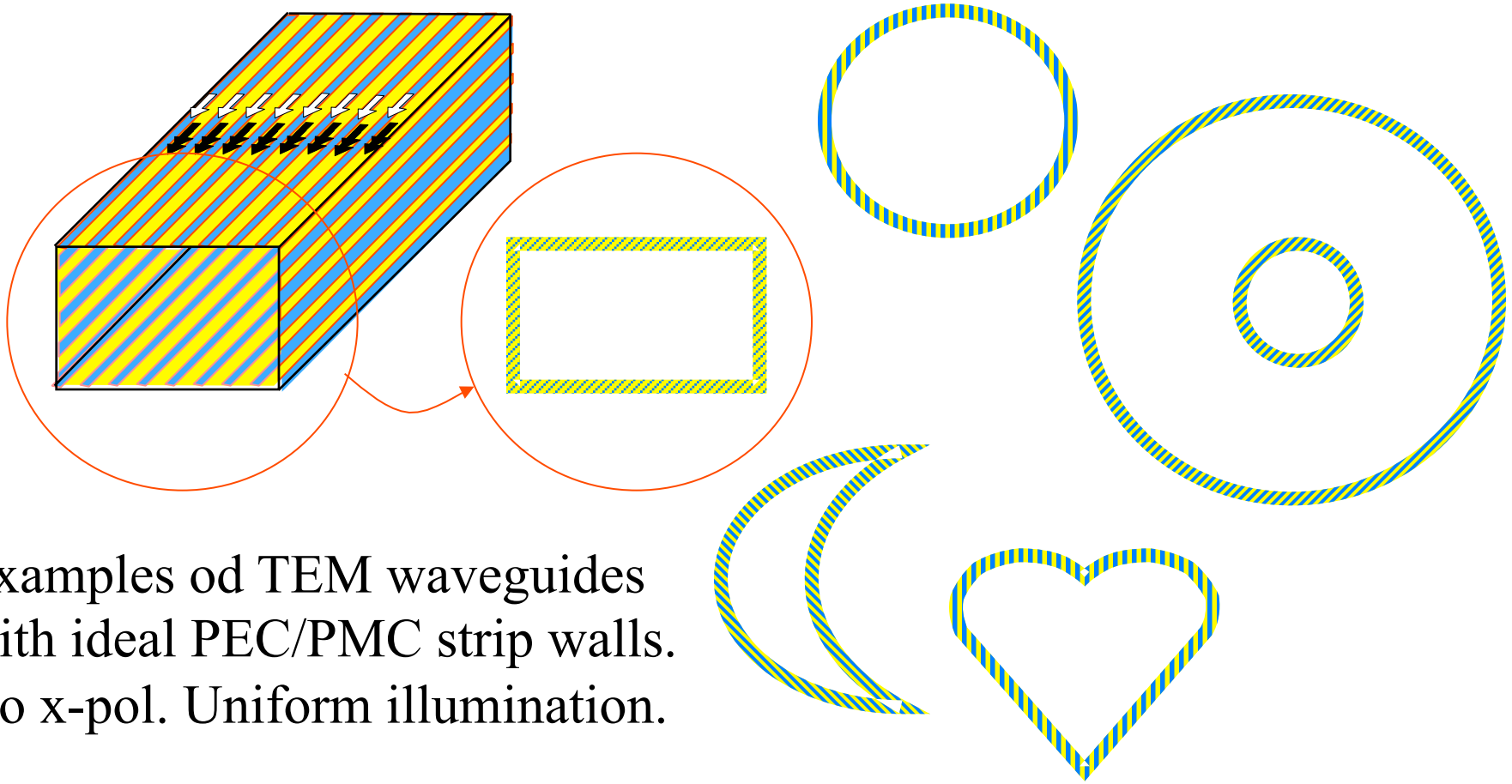
Plane wave in $\hat{l}$ direction :

$$\vec{E} = \left[E_n \hat{n} + E_t \hat{t} \right] e^{-jkl}$$

$$\vec{H} = \left[H_n \hat{n} + H_t \hat{t} \right] e^{-jkl} = \left[Z_0 E_t \hat{n} - Z_0 E_n \hat{t} \right] e^{-jkl}$$

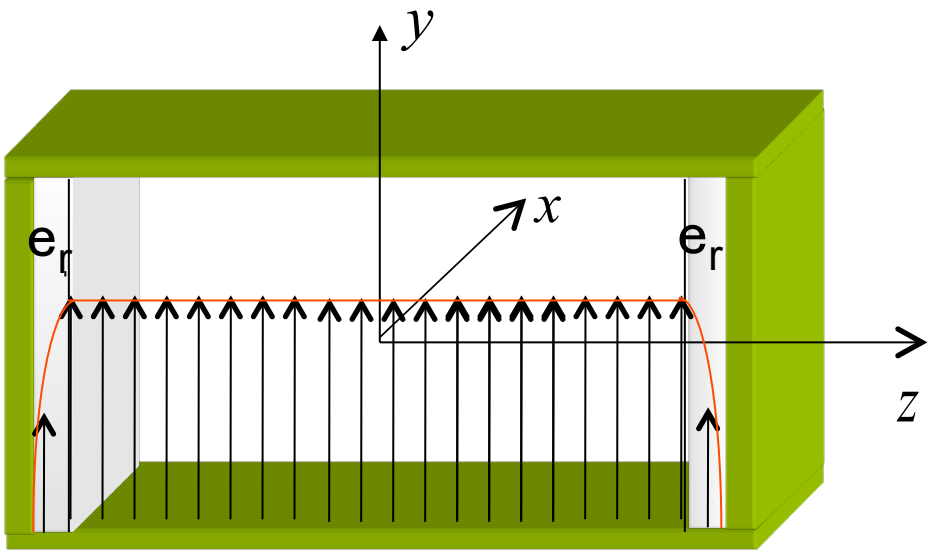
automatically satisfies boundary condition

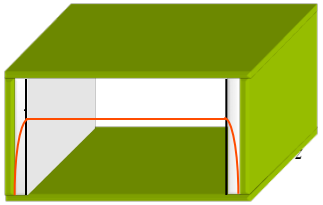
Therefore, hard cylinders of any cross-sectional shape are TEM waveguides (at center frequency)



Examples od TEM waveguides with ideal PEC/PMC strip walls. No x-pol. Uniform illumination.

Example of linearly polarized hard waveguide: Rectangular waveguide with dielectric-loaded walls

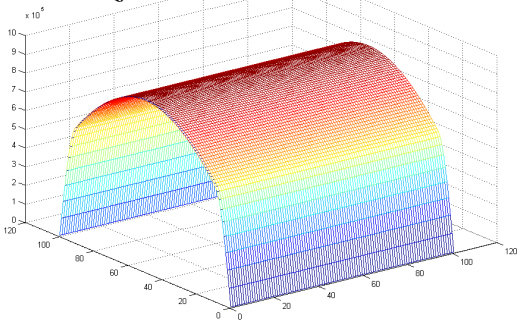




Analytical field solution in dielectric-loaded rectangular waveguide shows quasi-TEM performance at f_0.

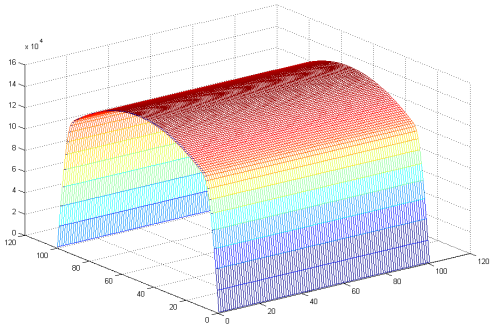
Relative Freq = 0.90

$k_{z3}a = 0.9314$



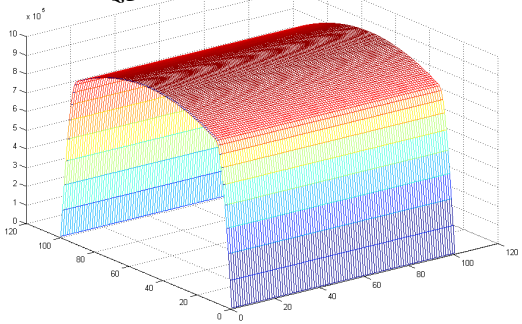
Relative Freq = 0.95

$k_{z3}a = 0.7079$



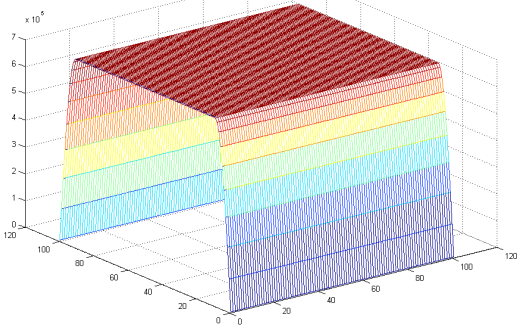
Relative Freq = 0.97

$k_{z3}a = 0.5719$



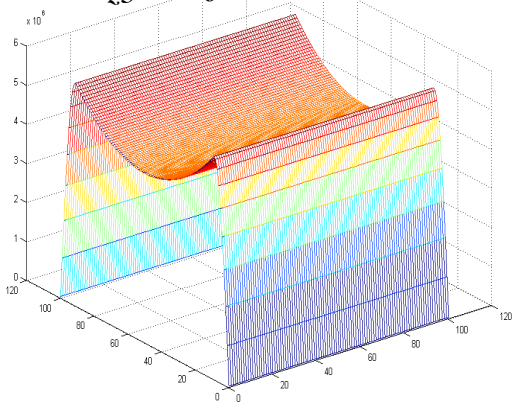
Relative Freq = 1.00

$k_{z3}a = 0.2014 + j0.1976$



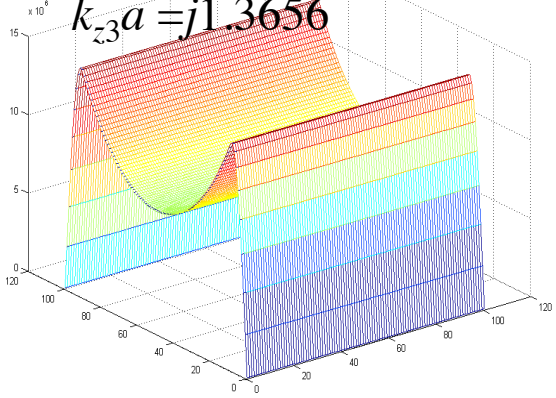
Relative Freq = 1.05

$k_{z3}a = j0.8656$



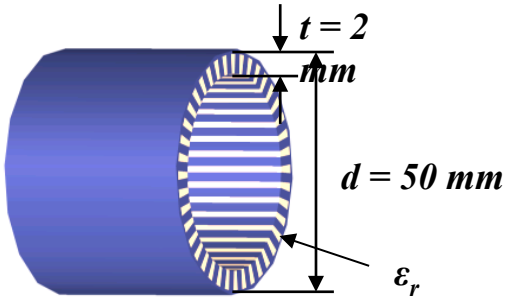
Relative Freq = 1.10

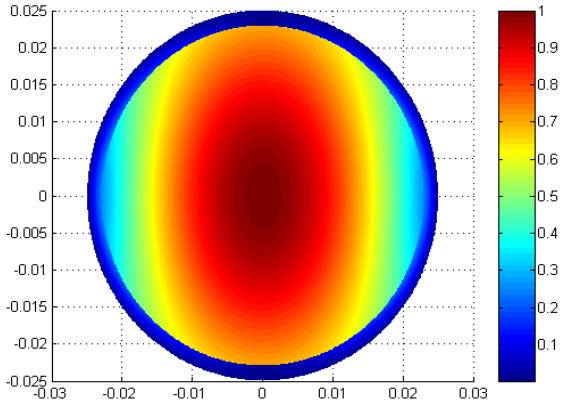
$k_{z3}a = j1.3656$



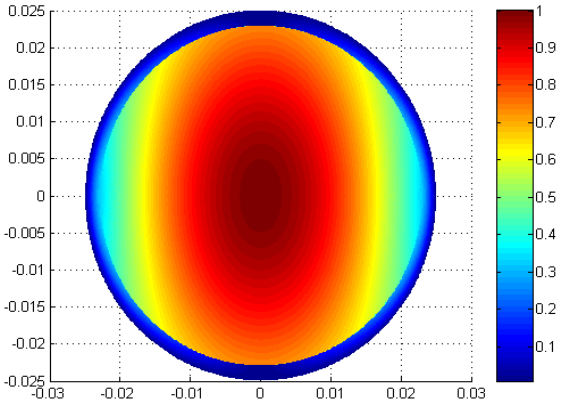
TEM frequency

Example: Analytical solution of 1st mode in circular hard corrugated waveguide

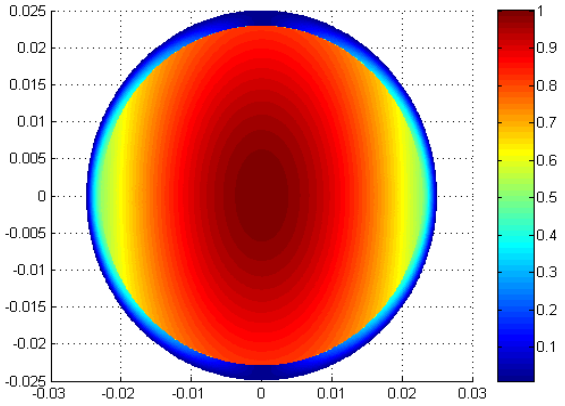




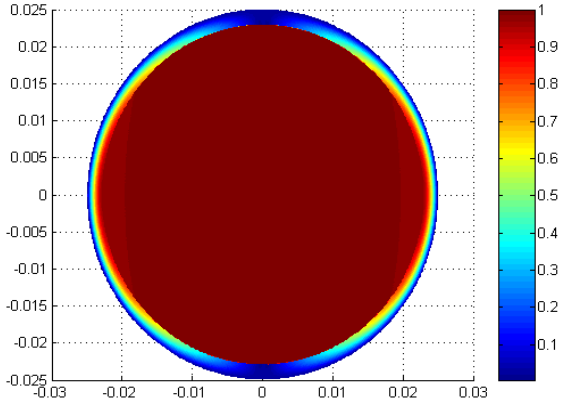
Frequency = 19 GHz



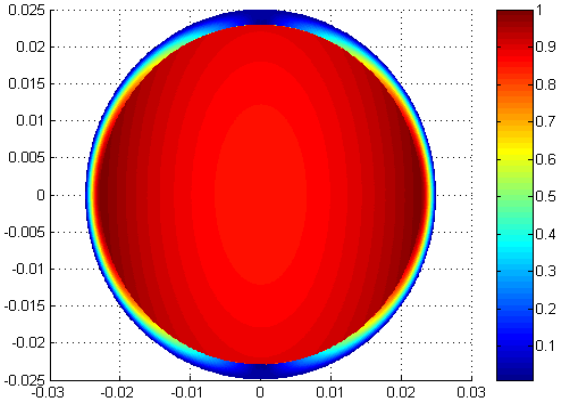
Frequency = 23 GHz



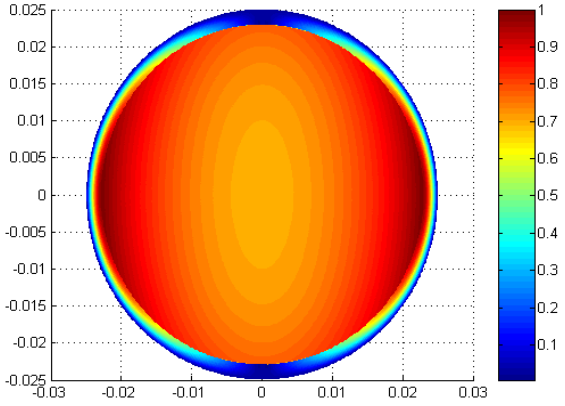
Frequency = 27 GHz



TEM Frequency = 29.5 GHz



Frequency = 30.5 GHz



Frequency = 31 GHz

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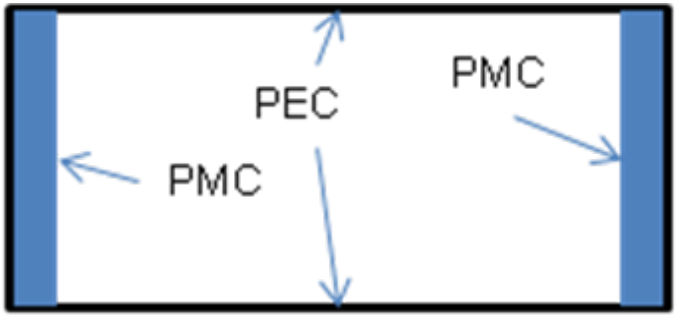
Gap waveguide basic geometry

Narrowband
hard waveguide [44]:



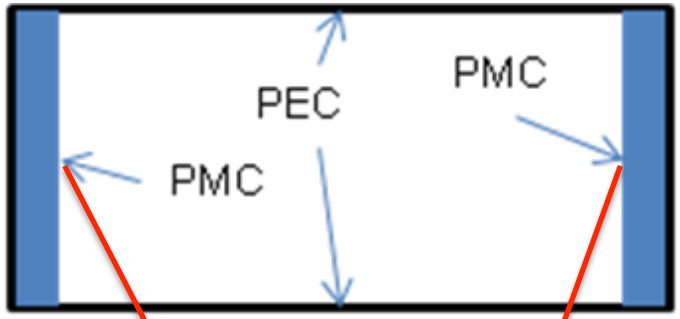
a) Original linearly polarized hard waveguide

Wideband gap
waveguide with
parallel-plate
CUT-OFF
or STOPBAND:

b) Ridge gap waveguide

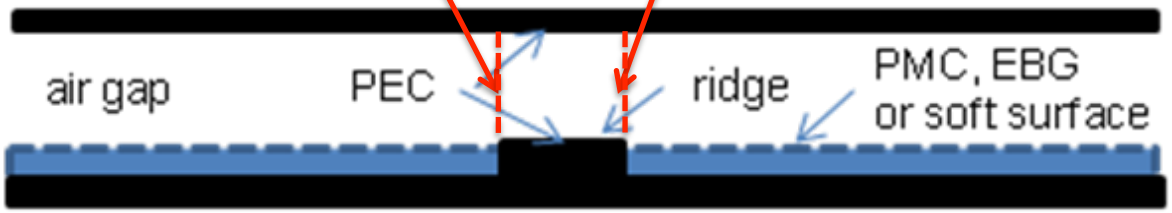
Gap waveguide basic geometry

Narrowband hard waveguide:



a) Original linearly polarized hard waveguide

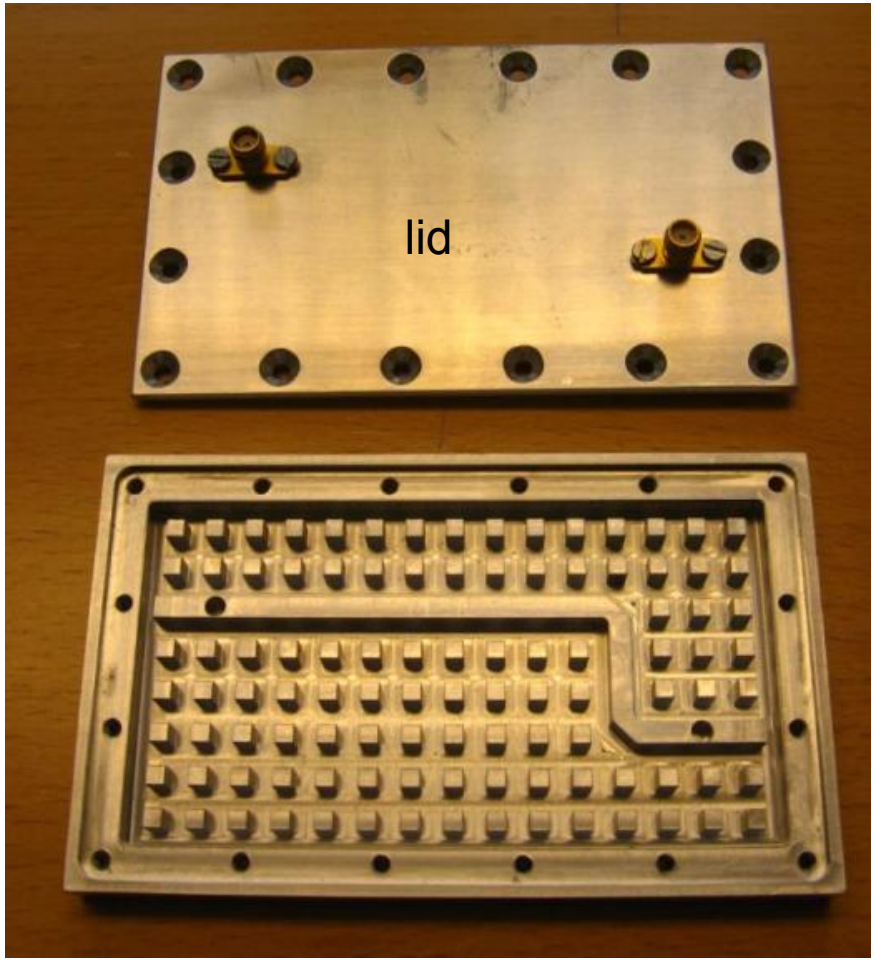
The parallel-plate stopband creates wideband virtual PMC walls:



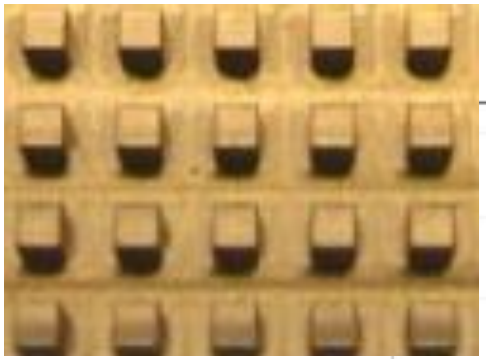
b) Ridge gap waveguide

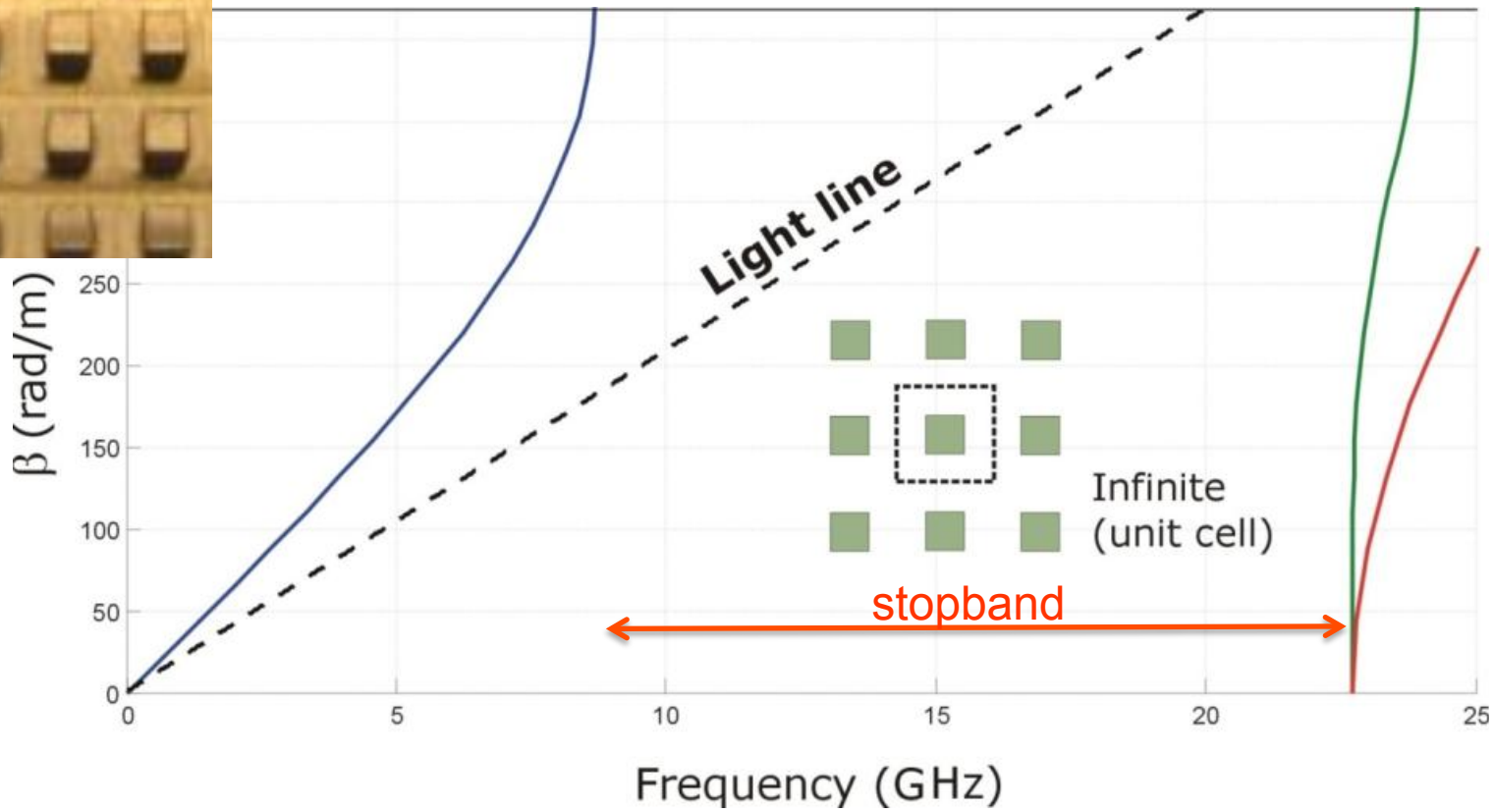
Gap waveguide demonstrator

- Ridge gap waveguide
- Bed of nails to provide parallel-plate cut-off
- Coaxial feeding (for simplicity only in 1st demonstrator)
- Demonstration at 15 GHz
- Woks when lid is on top, with a gap between lid and pins/ridge.

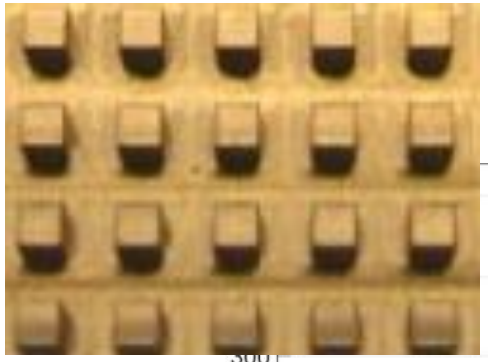


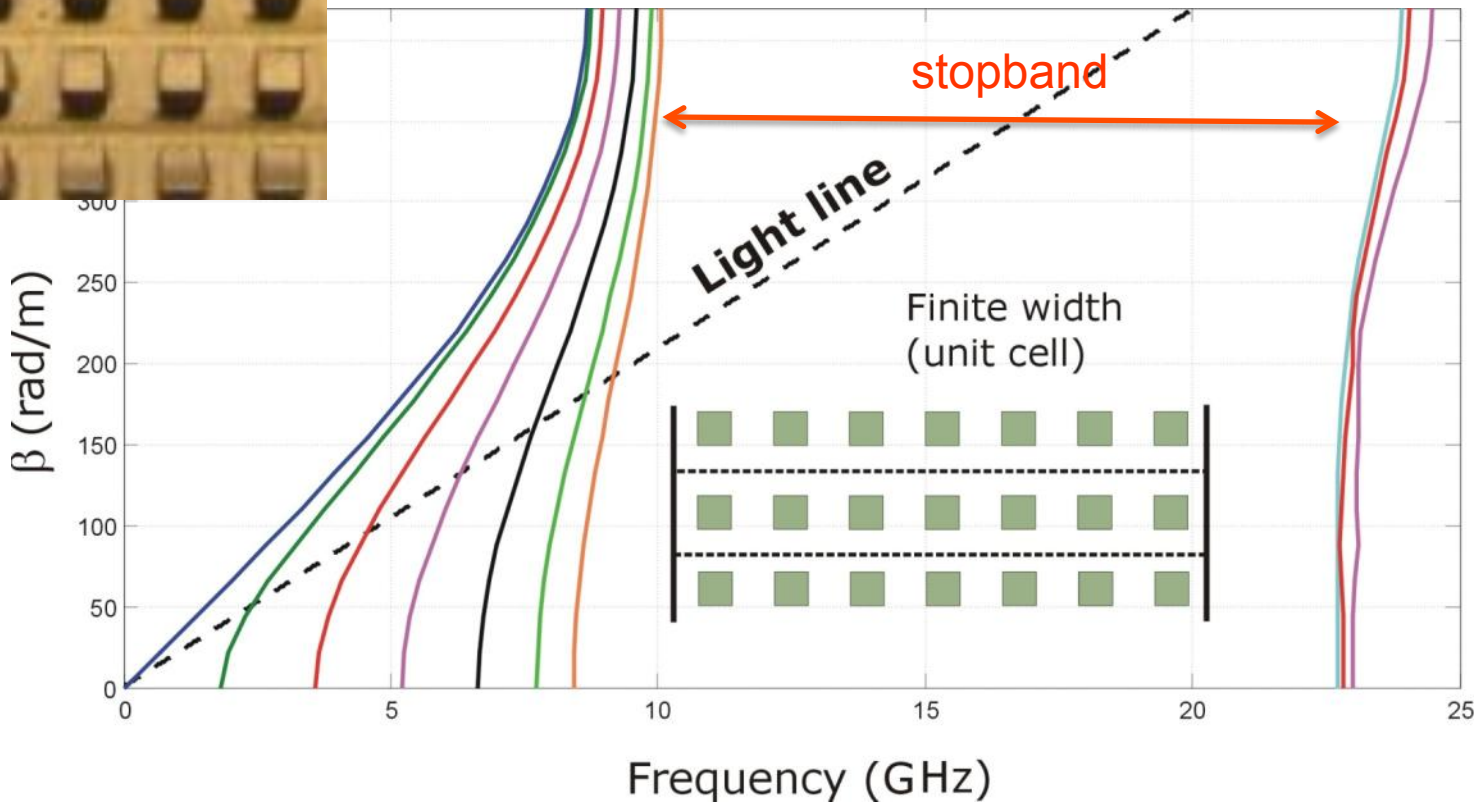
Dispersion diagram of unit cell showing stopband of parallel-plate modes [50] by using bed of nails as EBG/PMC surface and PEC lid above it



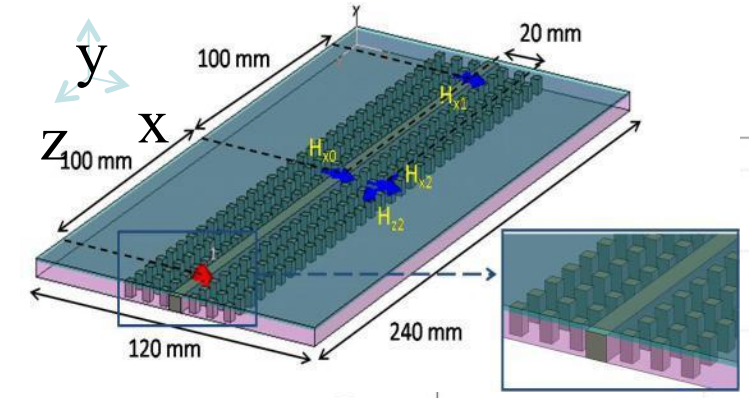


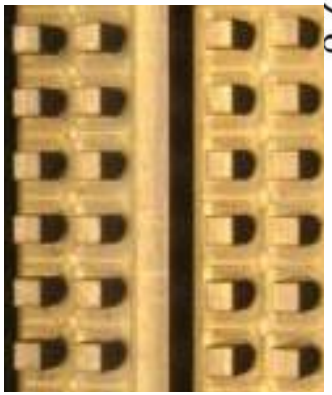
Dispersion diagram of pin-surface gap waveguide if there is no ridge, PMC sidewalls, and PEC lid on top

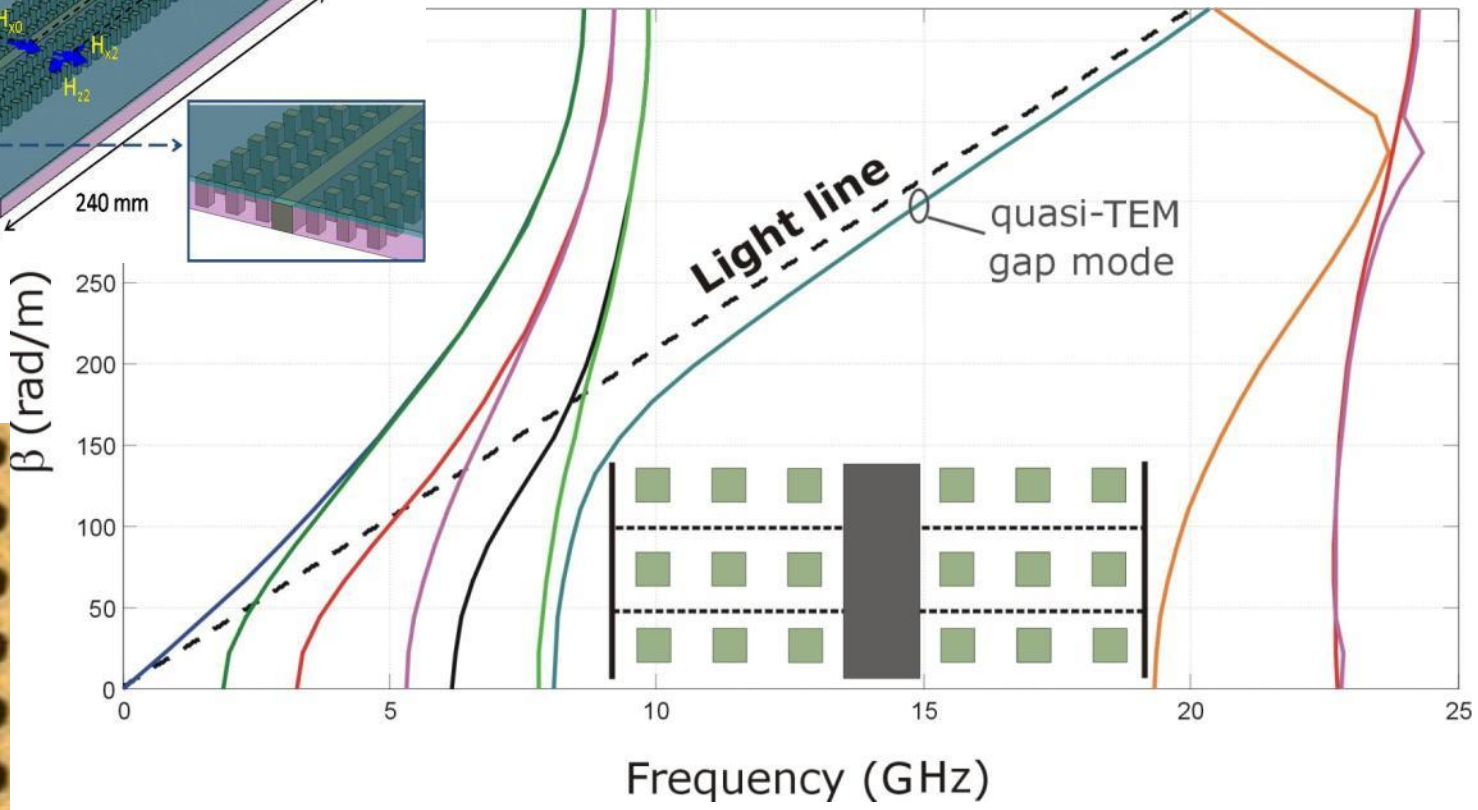




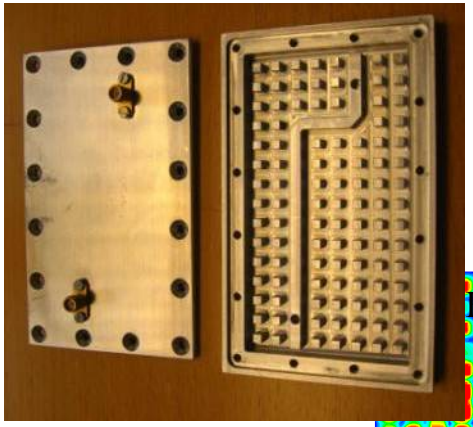
Dispersion diagram of ridge gap waveguide with PMC sidewalls and lid on top [46]

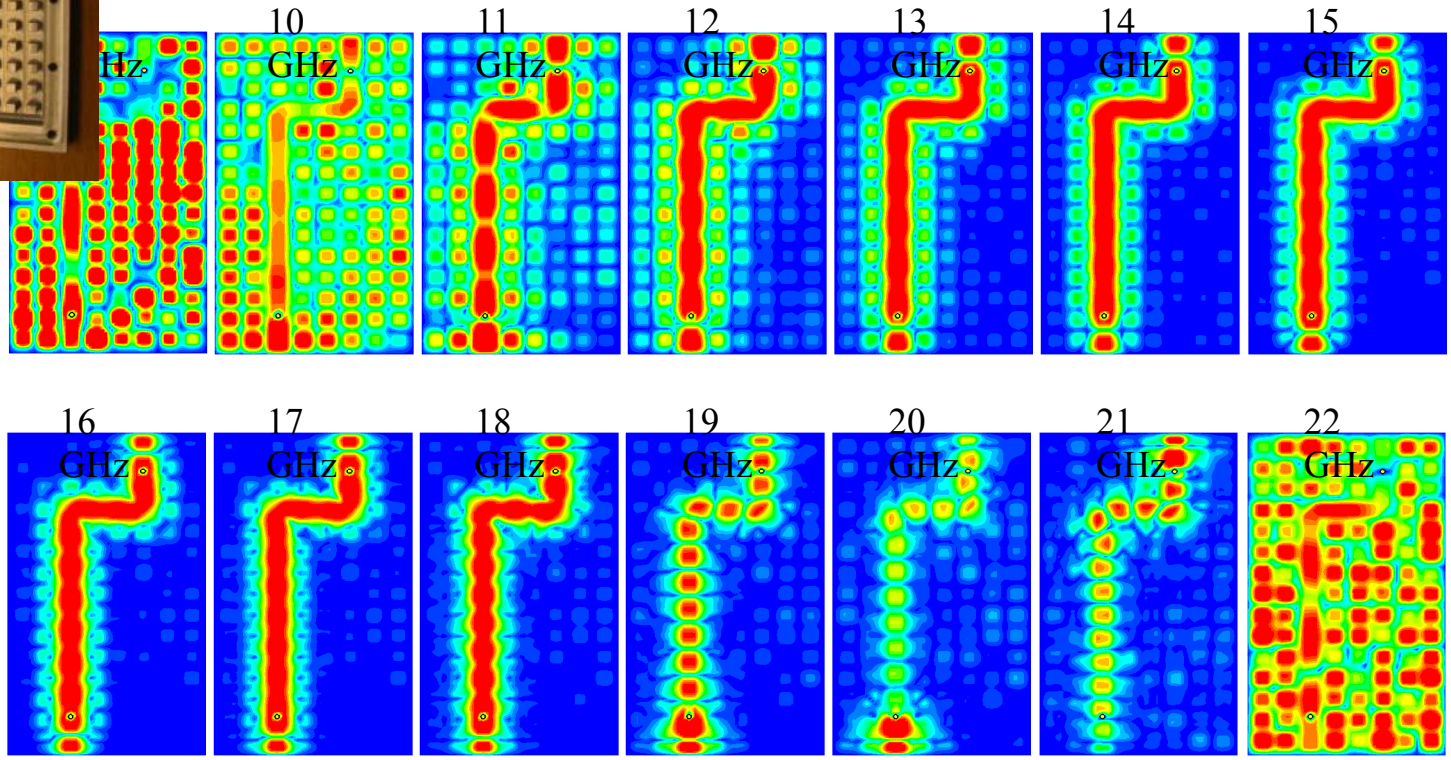






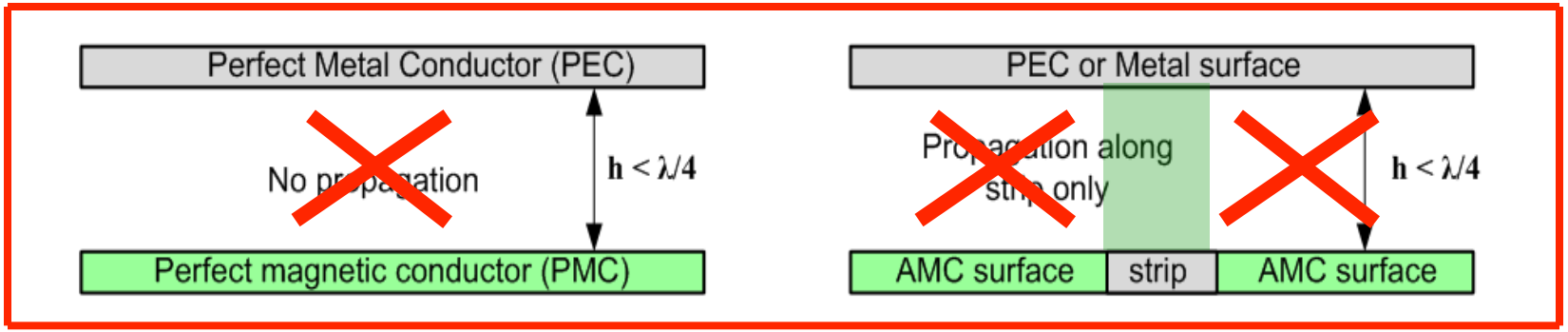
Simulated field distribution
in ridge gap waveguide.
We see the quasi-TEM mode following the
ridge between 11 and 21 GHz [51].





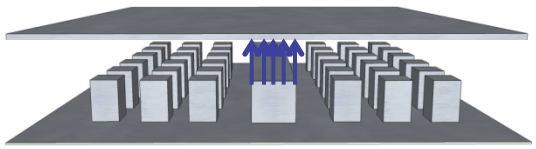
Three different gap waveguide types

- Principle of operation of gap waveguides (Cross sectional view):

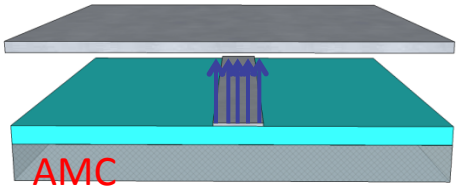


- 3 types of Gap Waveguides:

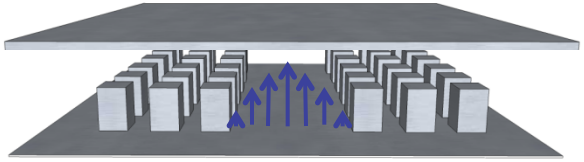
Ridge Gap Waveguide
Quasi-TEM mode



Microstrip Gap Waveguide
Quasi-TEM mode



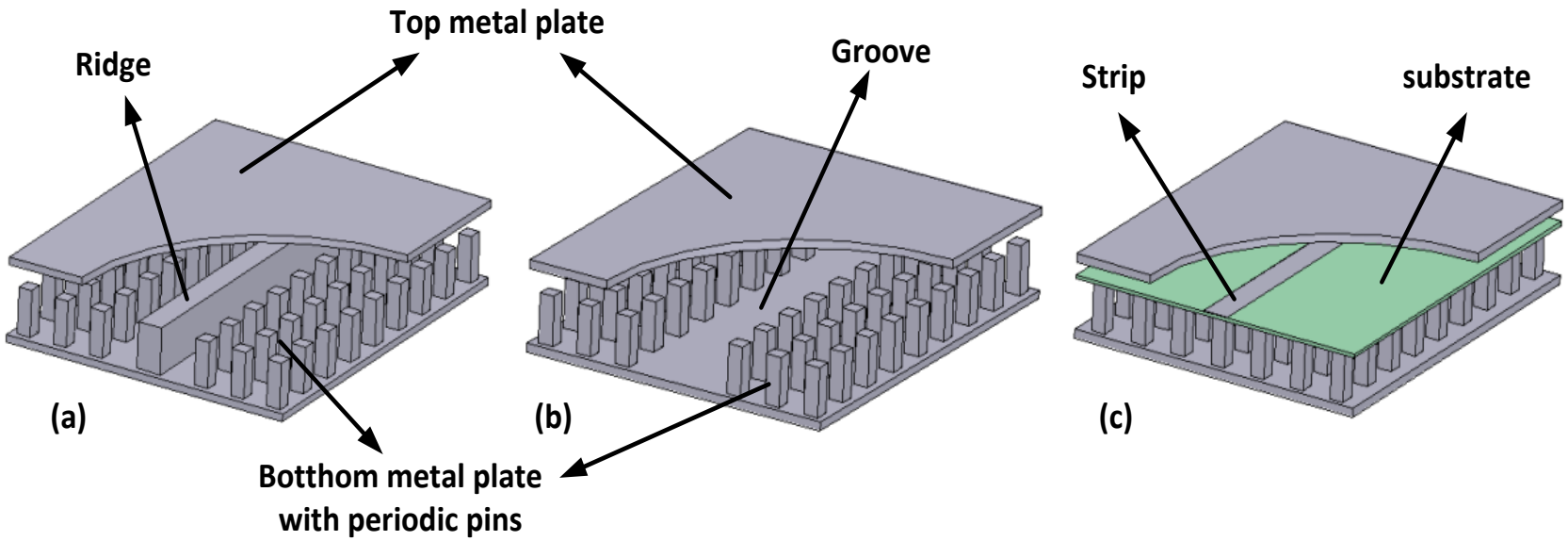
Groove Gap Waveguide
TE mode



No electrical contact between the 2 plates is required

Three types of Gap Waveguides [49]:

Ridge, Groove, Microstrip Gap waveguides



Motivation for research

- Applications above 30 GHz require new transmission lines
  - 60 GHz, E-band, Radio astronomy, Earth observations, environmental surveillance, communication, imaging (medical and security)
- Problem: Hollow waveguides become expensive
  - Manufacturing in split blocks requires conducting joints
  - Too small hole diameter
- Problem: Microstrip-type lines are lossy
- Ground-braking solution: Gap waveguide
  - Only metal, no dielectric
  - No conducting joints needed
  - Can be manufactured by low-cost milling, molding, etching or die casting

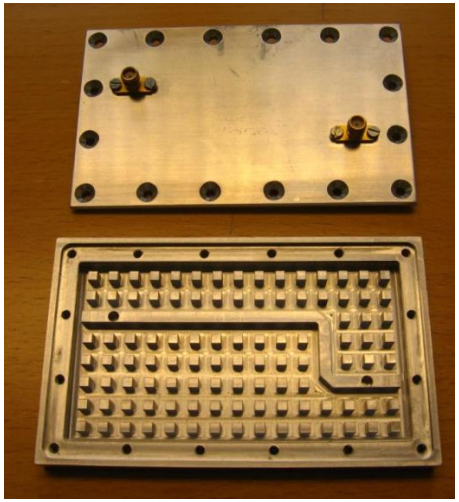


Illustration of losses for different printed microstrip techologies

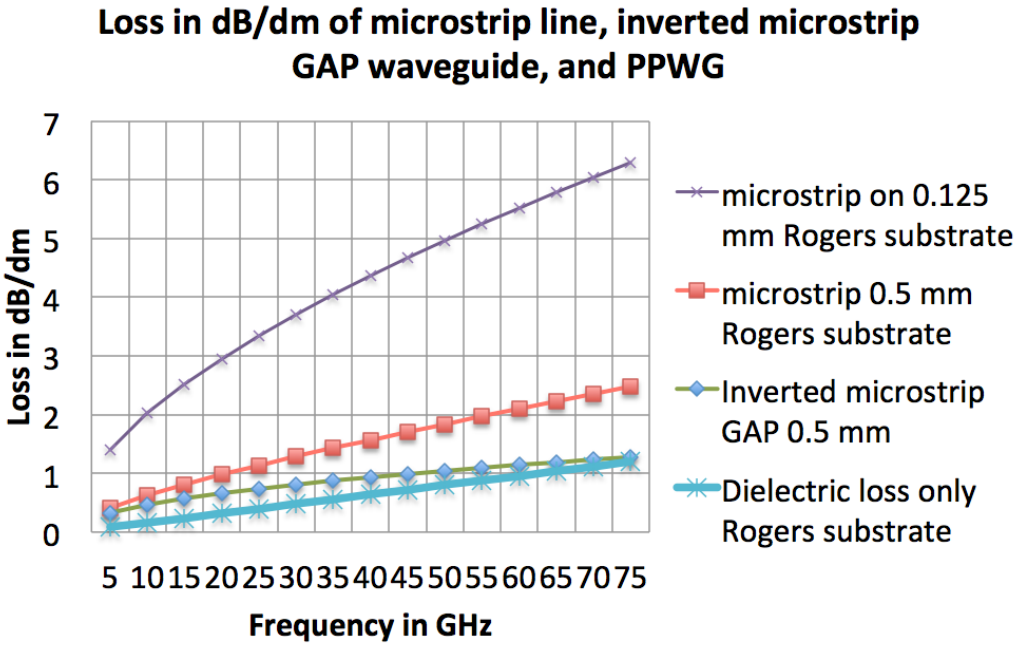
The curve for microstrip line on 0.125 mm Rogers substrate is from the manufacturer. We see that the loss in the metal is about 4.5 times larger than the loss in the substrate at 60 GHz. It works up to 60 GHz without much loss in surface waves.

According to theoretical formulas loss in dielectrics does not change with dimensions, whereas losses in metal as well as surface waves are inversely proportional to dimensions. Therefore, the maximum frequency of a 0.5 mm substrate is 74/4=18.5 GHz.

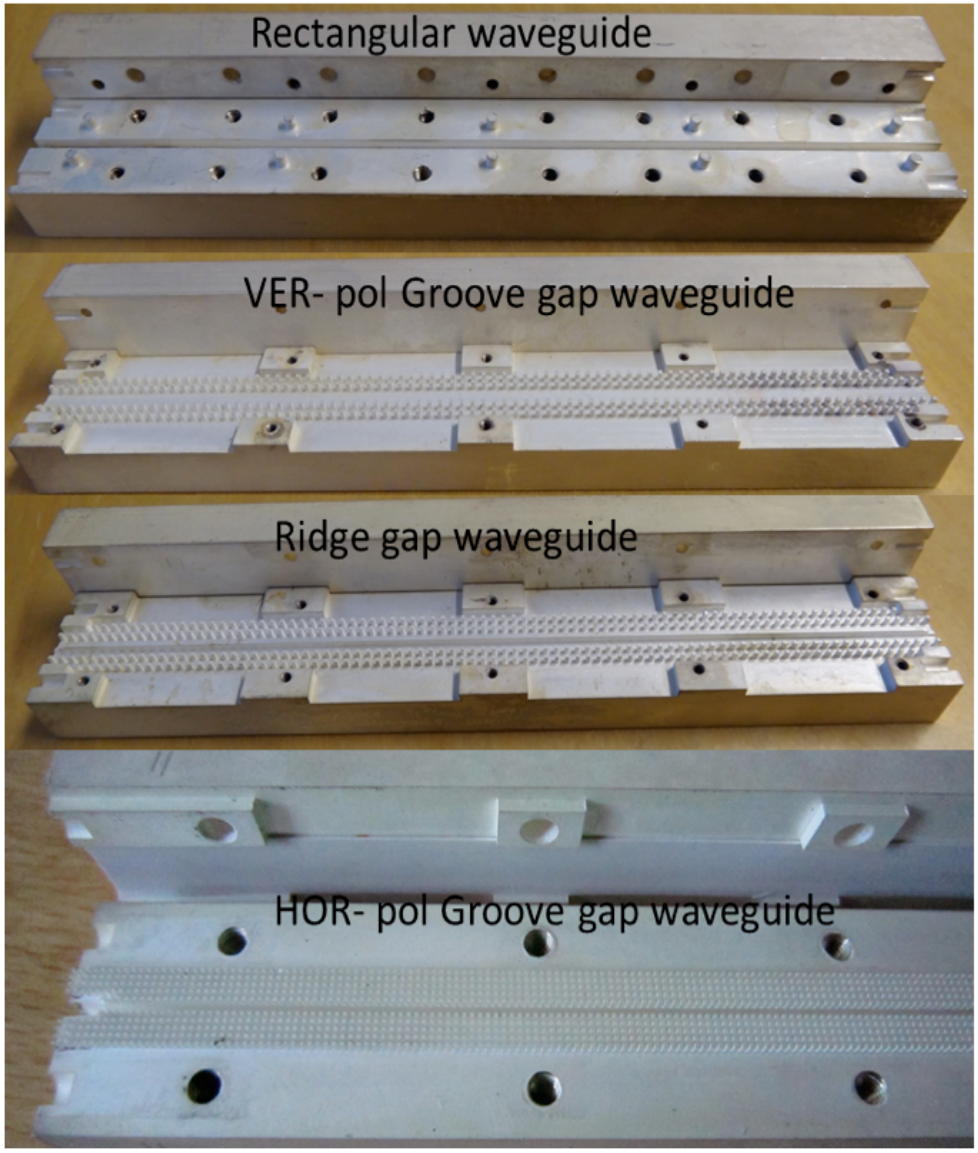
For gap waveguides there will never be surface waves, and the maximum dimension is determined by the strip width.

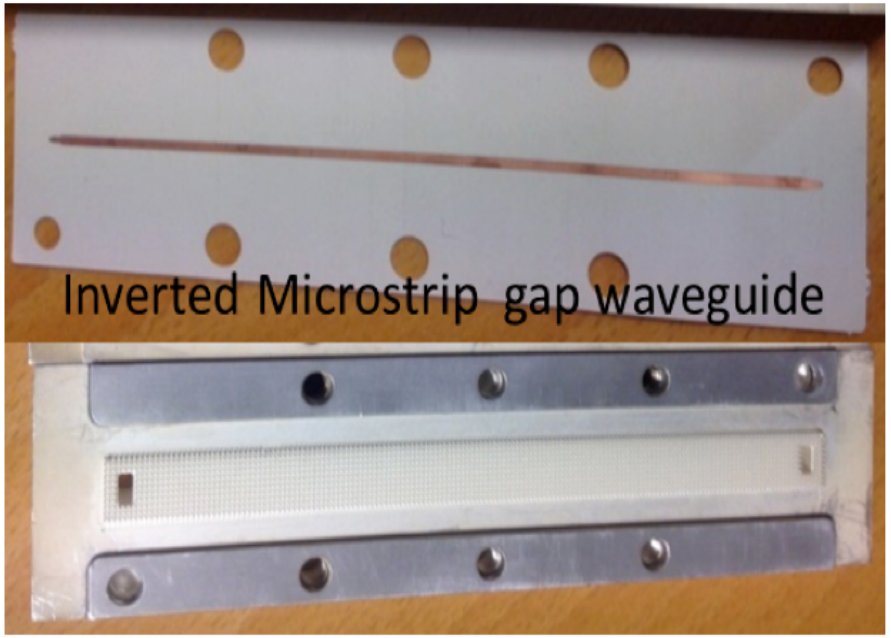
Therefore, a microstrip **gap** waveguide can be used with 0.5 mm width up to 60 GHz, giving a total loss reduction of more than a factor 2 as seen.

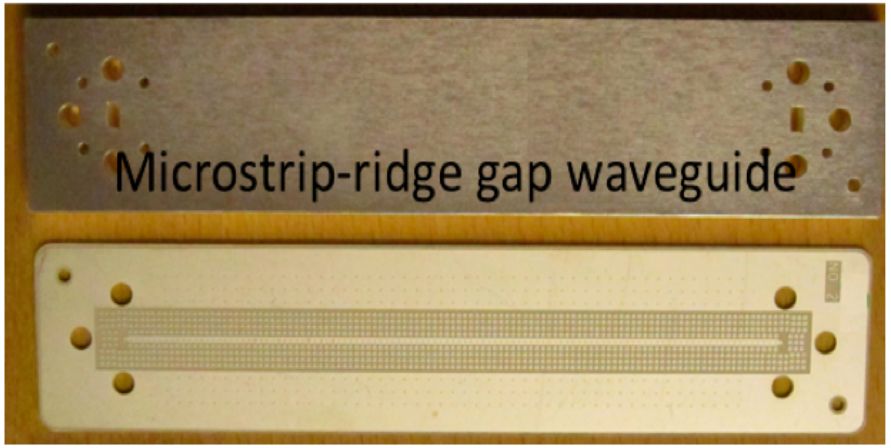
The loss can be reduced further to mainly conductive losses by using inverted microstrip gap waveguide, giving 1.2 dB/dm at 60 GHz. In practice there is still some dielectric losses in this solution.



Different 60 GHz waveguide [56]







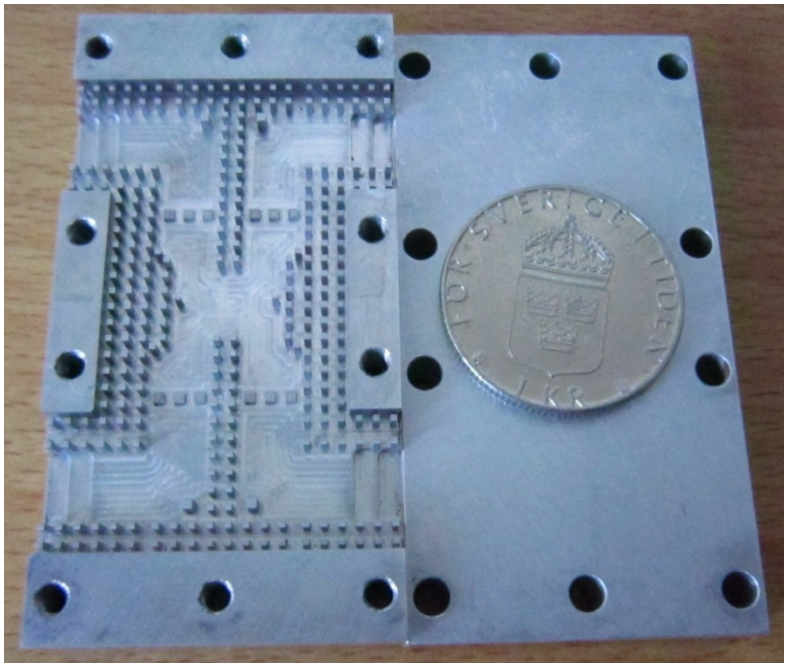
Losses in the waveguides on the previous page [56], compared to microstrip line and SIW

Prototype (frequency)	Simulated loss (dB/cm)	Measured min. loss (dB/cm)	Measured max. loss (dB/cm)
Rect. Waveguide (50-75 GHz)	0.0136	0.0295	0.042
VER-pol Groove (50-75 GHz)	0.019	0.03	0.0442
HOR-pol Groove (56-75 GHz)	0.036	0.05	0.058
Ridge gap (50-75 GHz)	0.0373	0.058	0.0705
Micro-ridge gap (56-68 GHz)	0.0805	0.162	0.23
Invert-micro. gap (56-72 GHz)	0.0934	0.21	0.288
Microstrip line (50-75 GHz) 0.127-0.2mm substrate	LCP ; 0.23	0.62	0.77
	Rogers4003; 0.271	0.7055	
Air filled SIW (50GHz)	0.0621	0.0615	
Rogers-5880, SIW (50GHz)	0.1727	0.172	

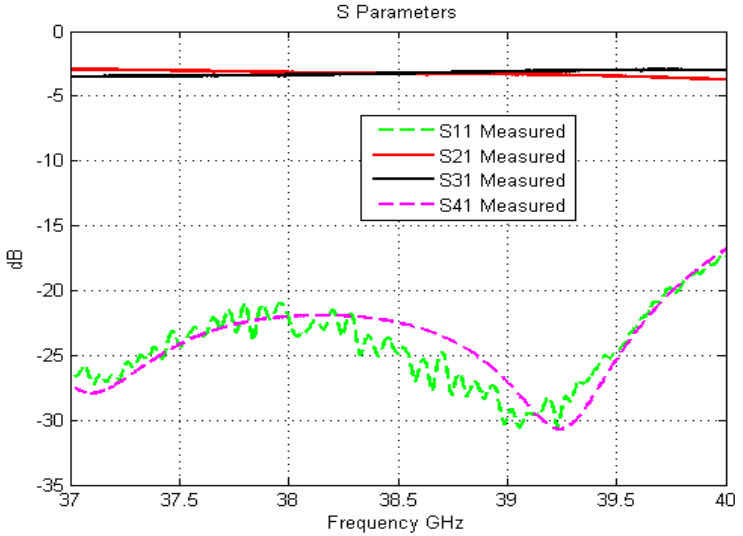
Example: Groove gap waveguide coupler

- Manufactured 3 dB coupler and measured results:

  - 4% BW for ± 0.25 dB amplitude imbalance between the two output ports
  - Phase difference of ± 2.5° over the entire bandwidth

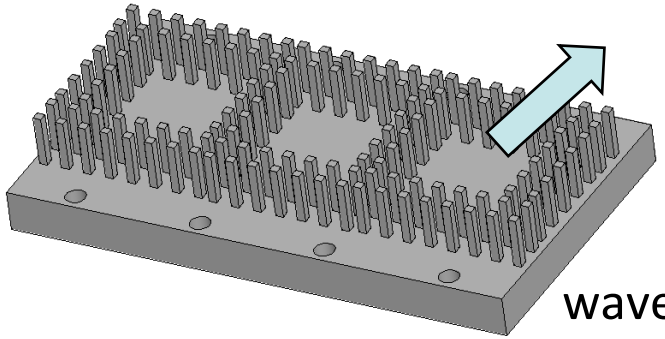


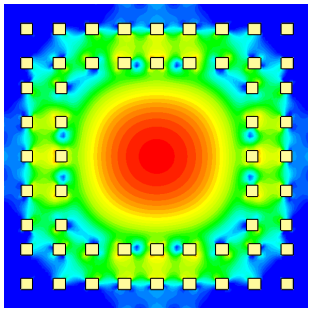
- Return loss and isolation better than 20 dB over the entire band



Example: groove gap waveguide filter [61]

- Coupled-cavity filter:

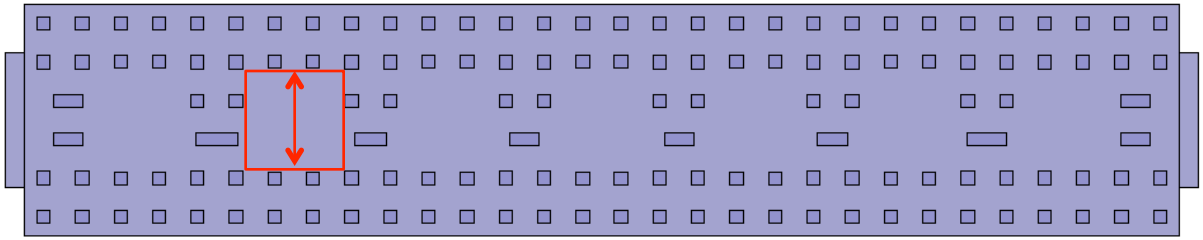




Groove gap waveguide resonator

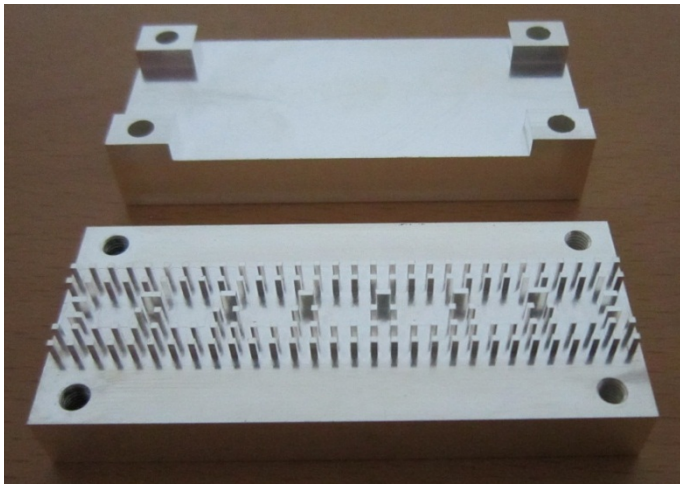
- Technique based on:
  - **Coupling coefficient (*K*)** between cavities
  - **External quality factor (Q_{ext})** of the in/out cavities
- Optimization

- Final design: 7th order filter in groove gap waveguide

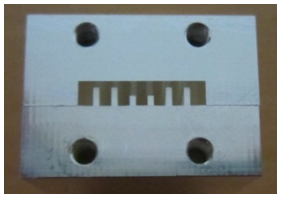


Example: Groove gap waveguide filter [61]

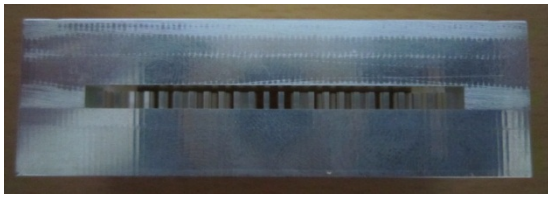
- Prototype: Silver-plated



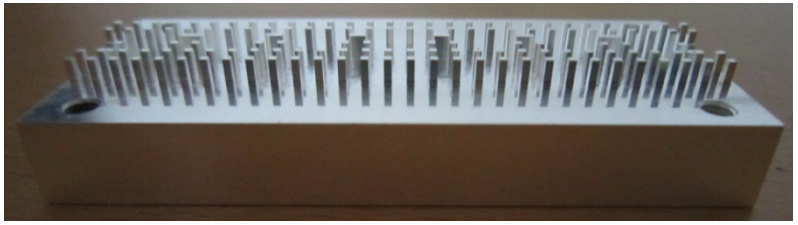
Top and bottom parts



Front view



Side view

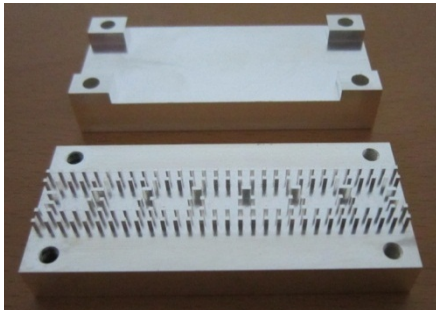


Bottom part

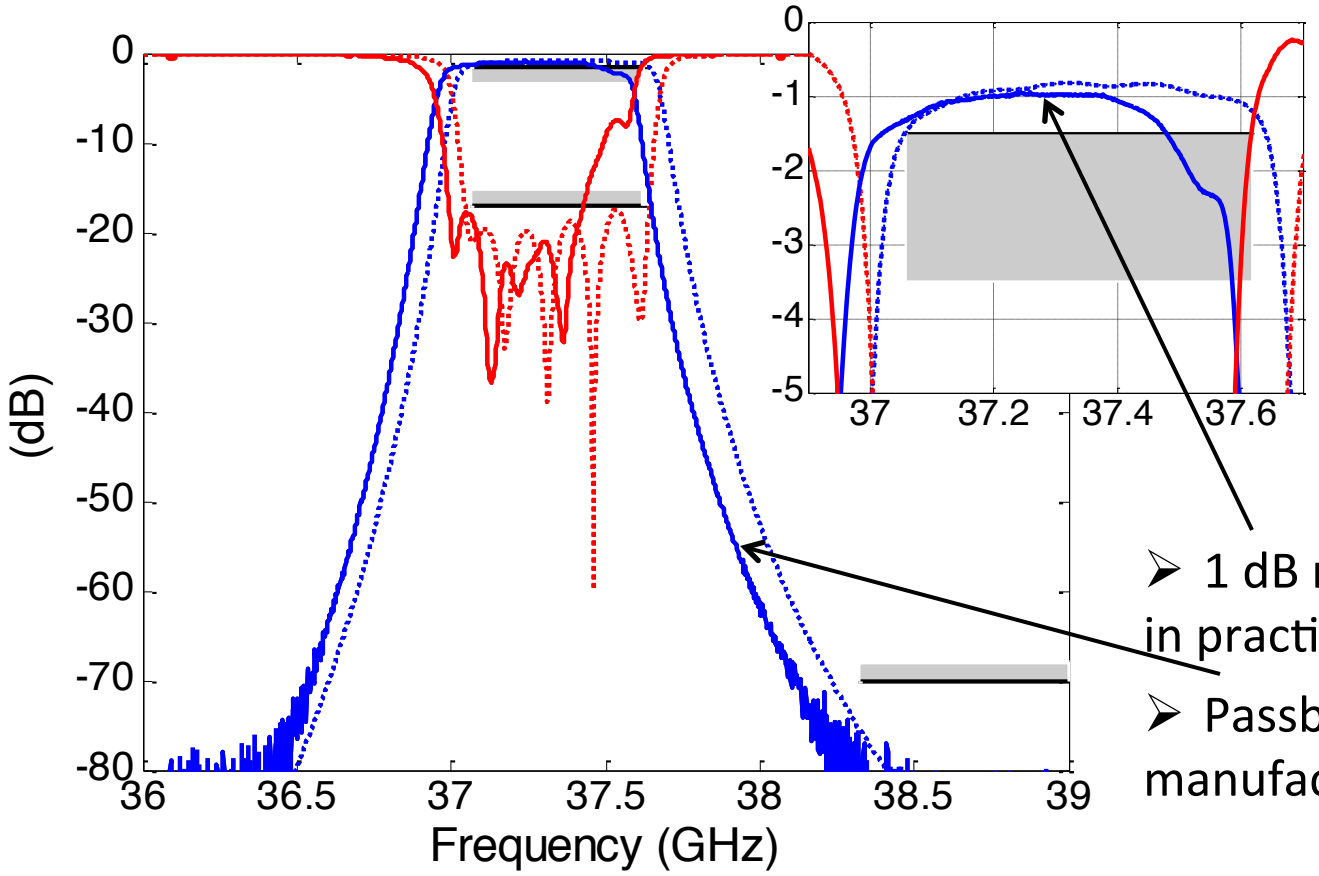
- Same performance as existing 38 GHz filter technology
- No electrical contact required between the top and bottom metal plates
- No metal sidewalls → less sensitive to temperature variations

	Frequency shift {-50°C,+70°C}
GAP filter	50 MHz (≈9%)
RW filter	60 MHz (≈11%)

Example groove gap waveguide filter

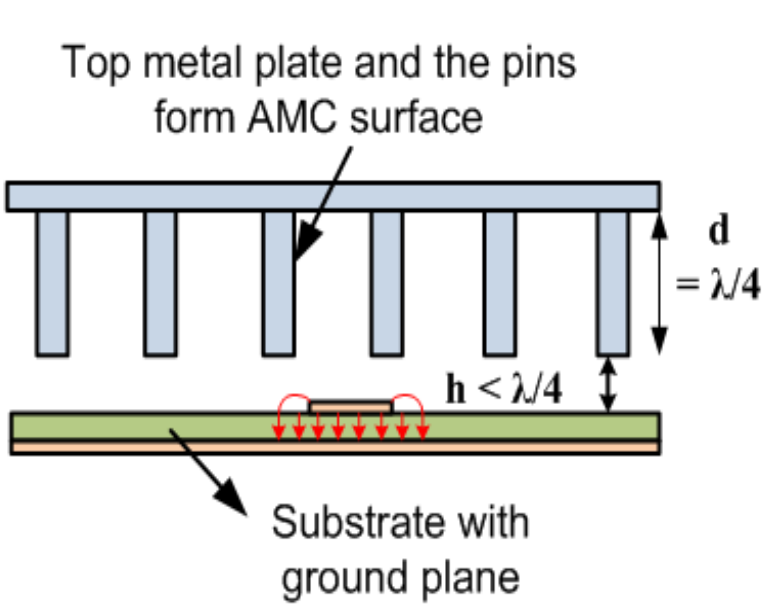


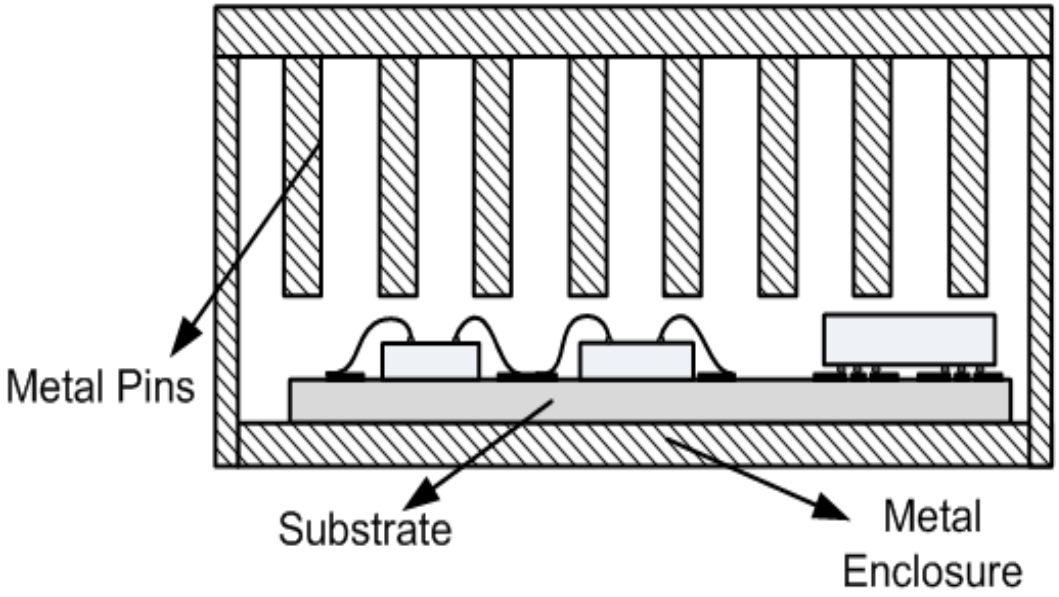
- Measured and simulated results:



- 1 dB minimum insertion loss in practice
- Passband is shifted due to manufacturing tolerances

PMC (pin lid) packaging of MMICs [64]



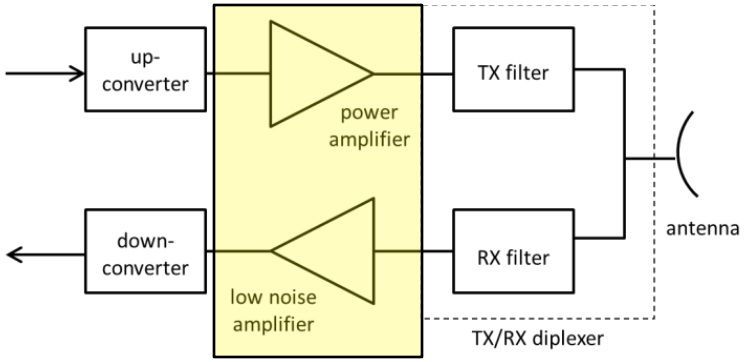


➢ The ground plane of the circuit board and the AMC lid creates a stopband for all possible unwanted parallel-plate modes

PMC (pin lid) packaging of MMIC [64]

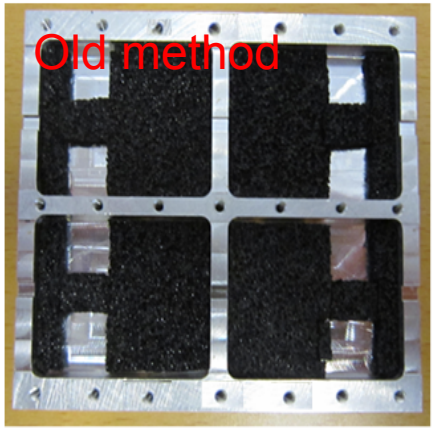
- Project: RF frontend at 38 GHz

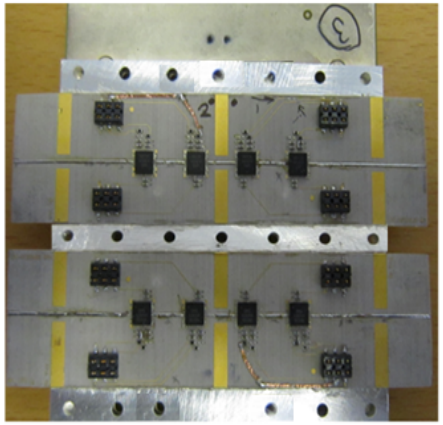
  ➢ Validation of MMIC packaging in real system



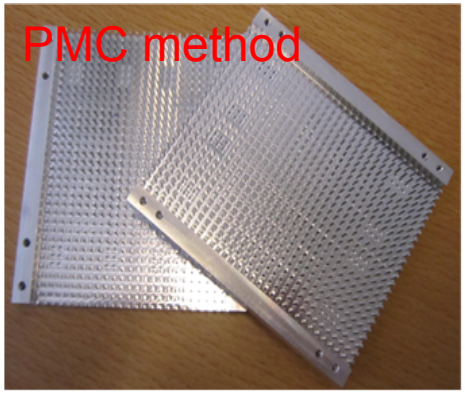
  ➢ 2 amplifier chains for TX/RX

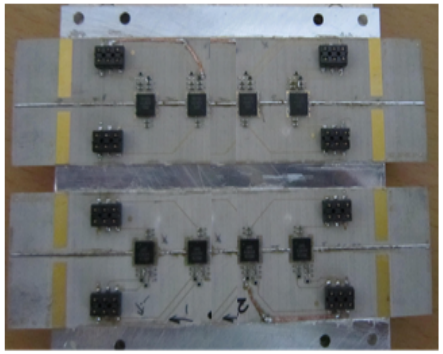
  ➢ Comparison with traditional shielding using metal walls and absorbers





Metal wall with Eccosorb

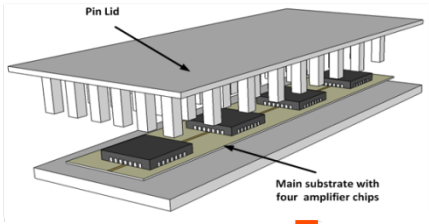


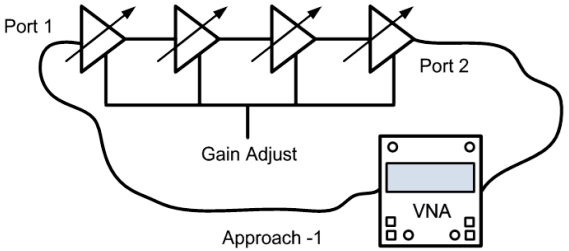


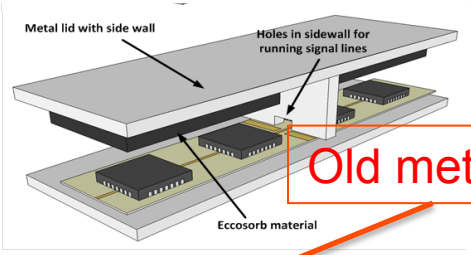
Two pin lids

PMC (pin lid) packaging of MMIC [64]

- VNA: Measured in/out isolation of single chain

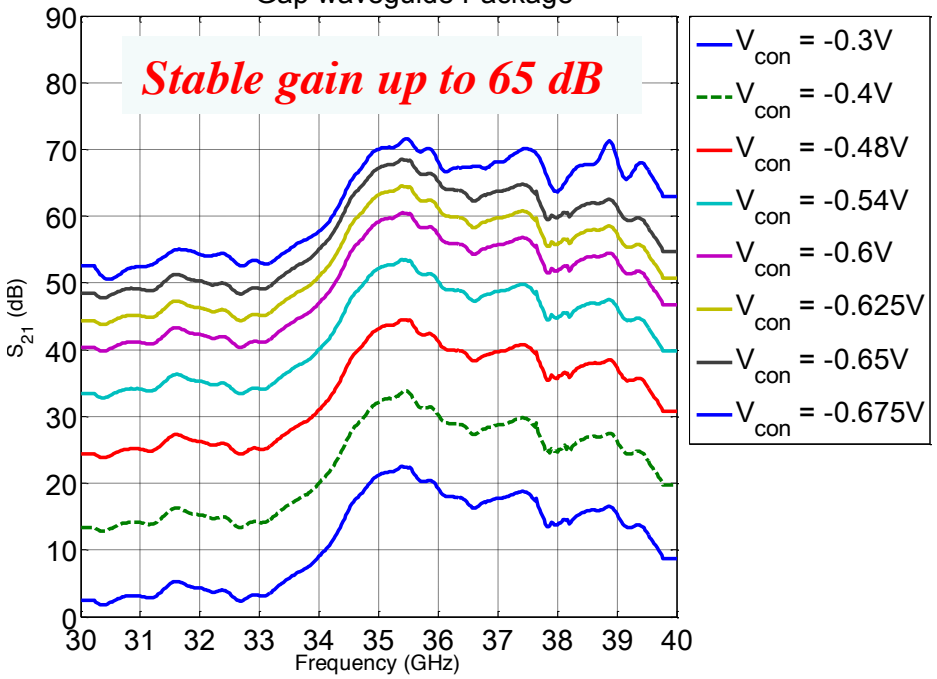




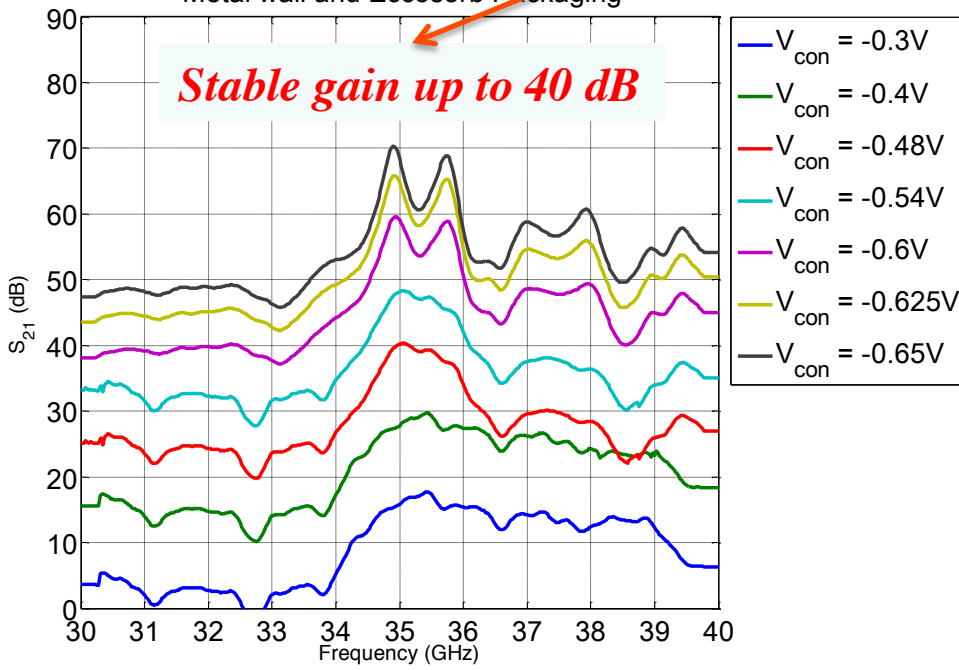


Old method

Gap waveguide Package

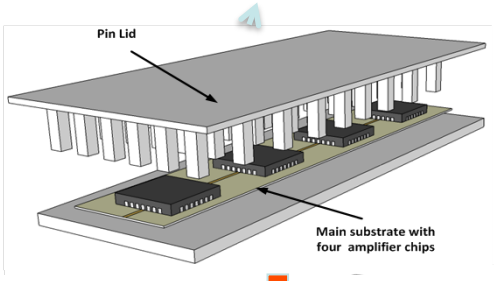


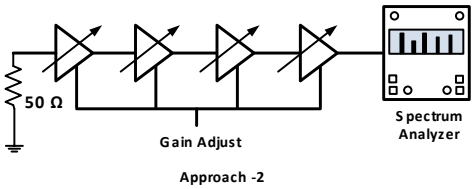
Metal wall and Eccosorb Packaging



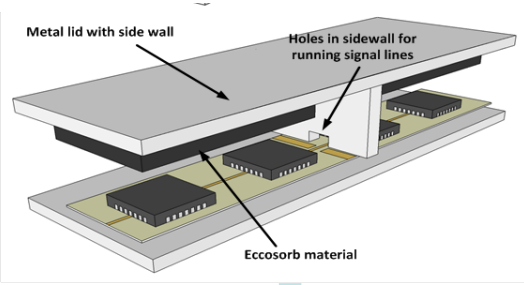
PMC (pin lid) Packaging of MMIC [64]

Spectrum Analyzer: Measured oscillation tendency of single chain

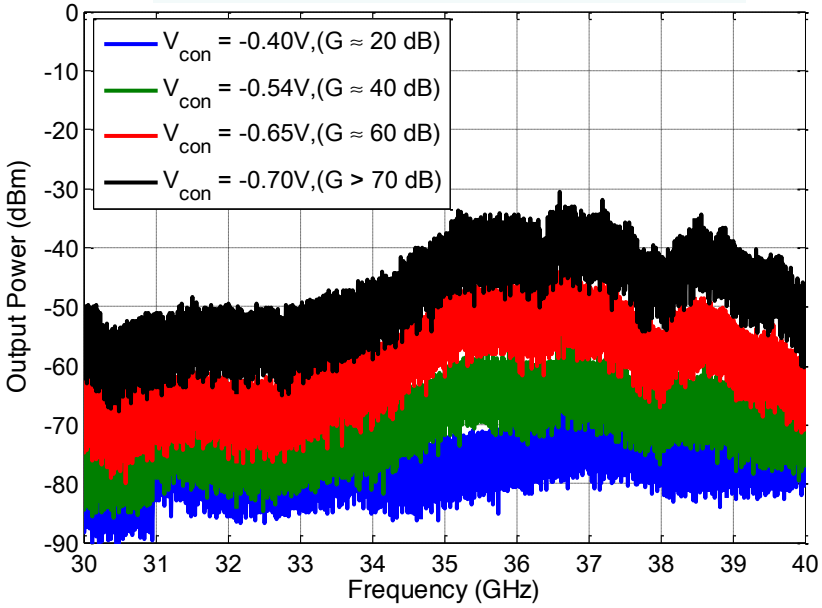




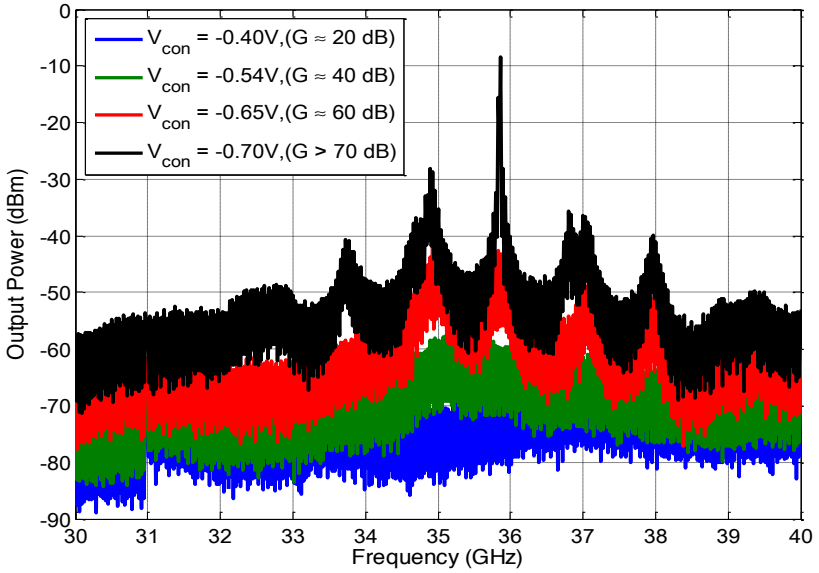
Approach -2



No oscillation up to 70 dB gain

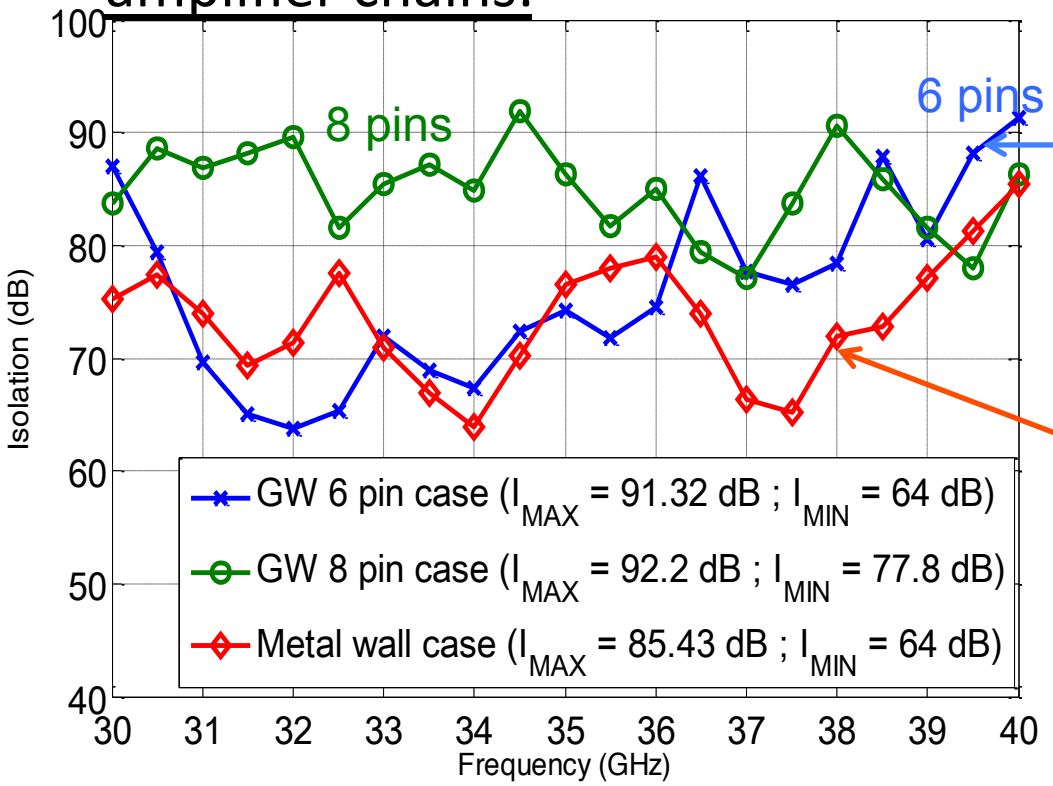


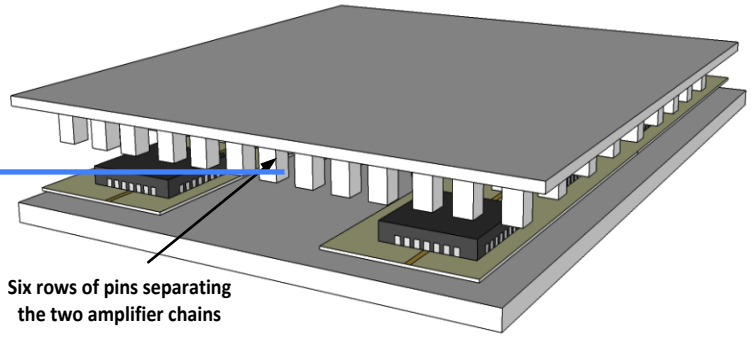
Oscillation tendency after 40 dB gain

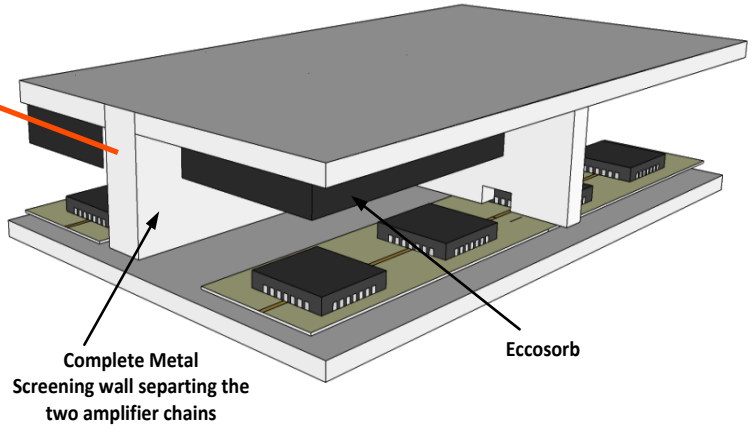


PMC (pin lid) packaging of MMIC [64]

- Measured isolation between side by side amplifier chains:





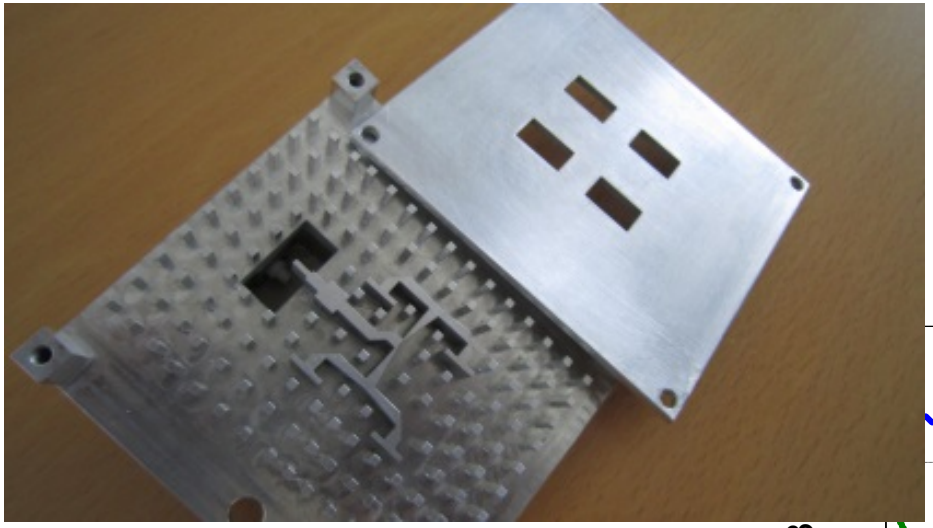


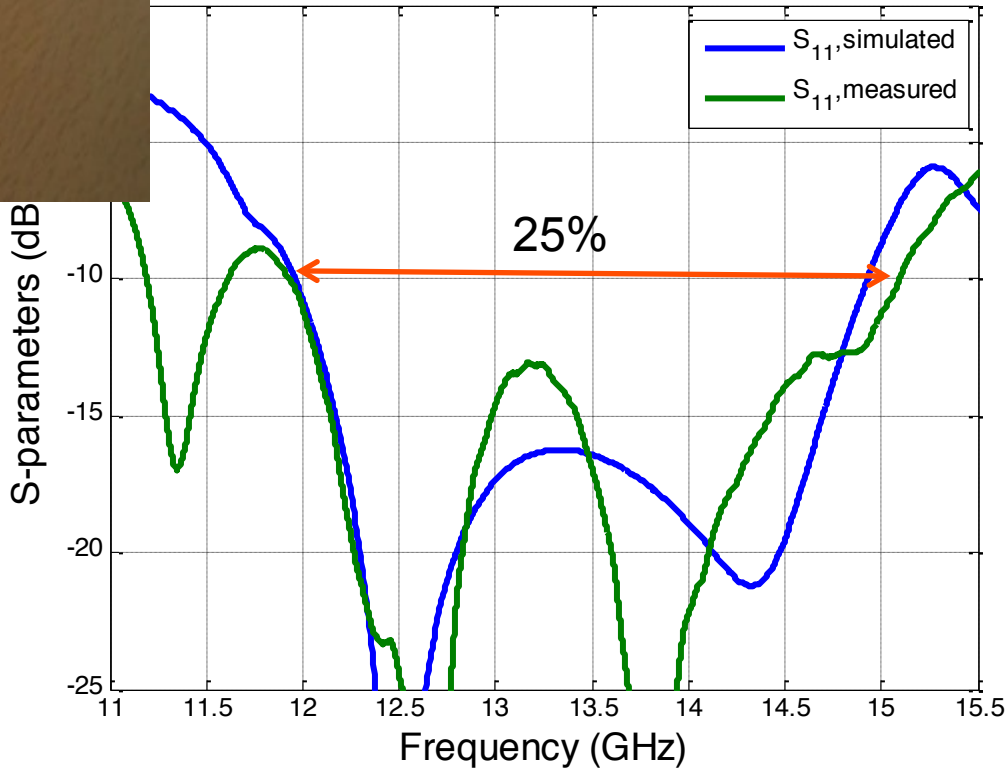
➢ Gap waveguide packaging is an improved packaging technique

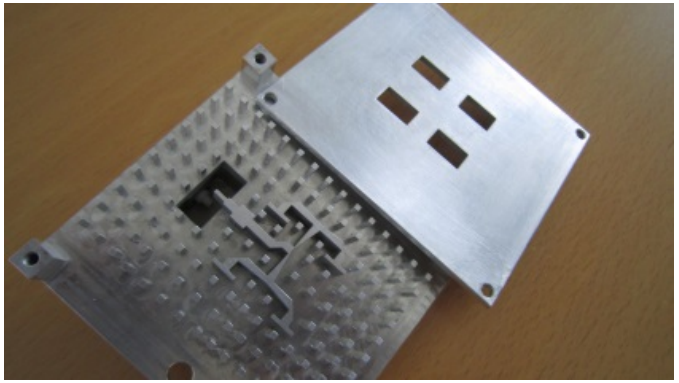
Content

- Introduction
- Definition of soft and hard surfaces 1988
- Soft surface and bandgaps since 1988
- Hard surface and cloaking in 1996
- Gap waveguides since 2009
- Gap waveguide antennas since 2012
- Wideband directive antennas at 60 GHz
- Summary and future
- Independent research by Erik Lier:
  Metamaterial-based horn-antennas based on soft and hard surfaces

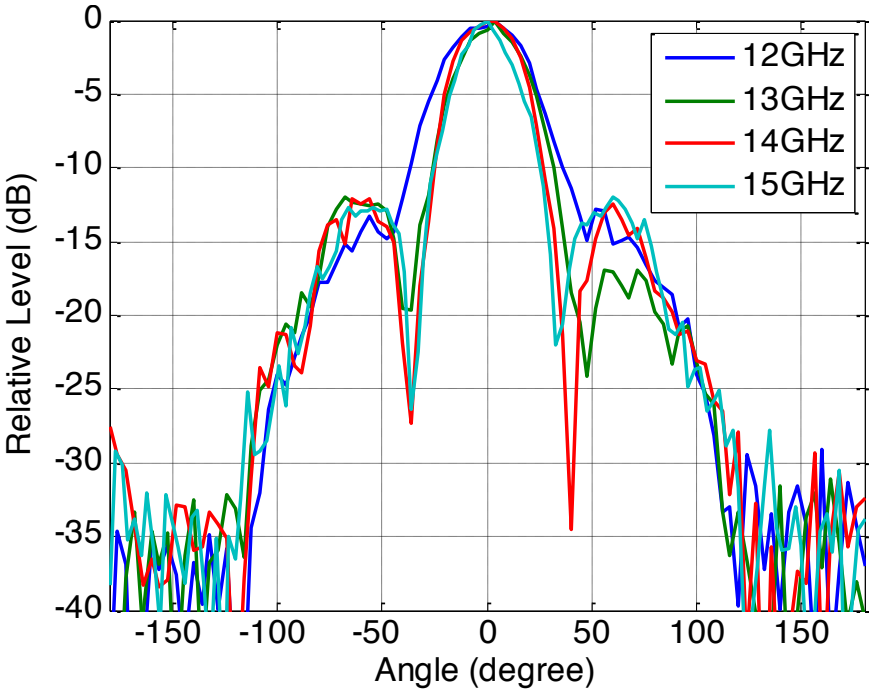
2x2 slot element for use in planar antenna array [57]



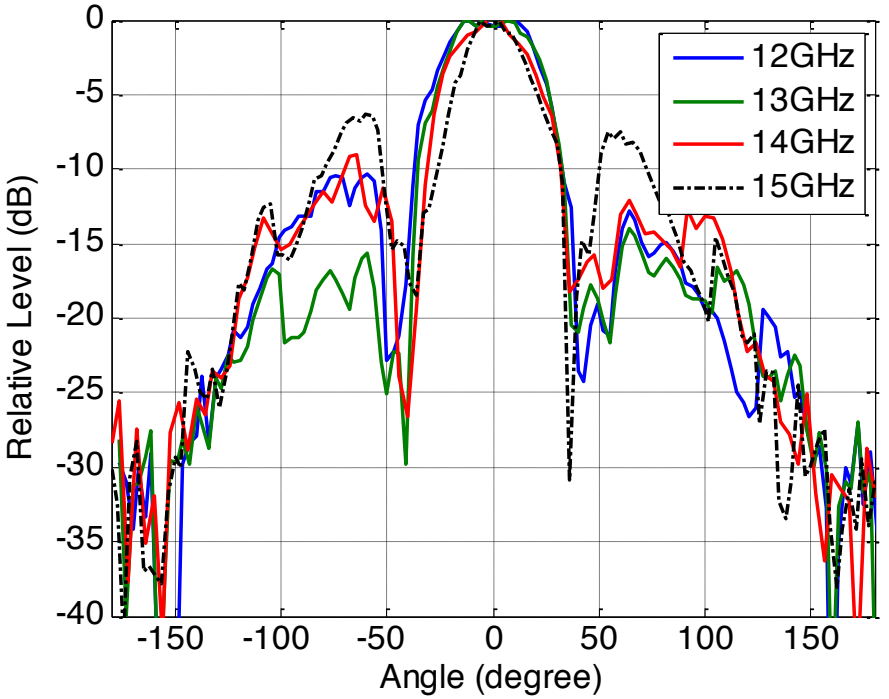




Measured patterns of 2 × 2 planar slot array [64]

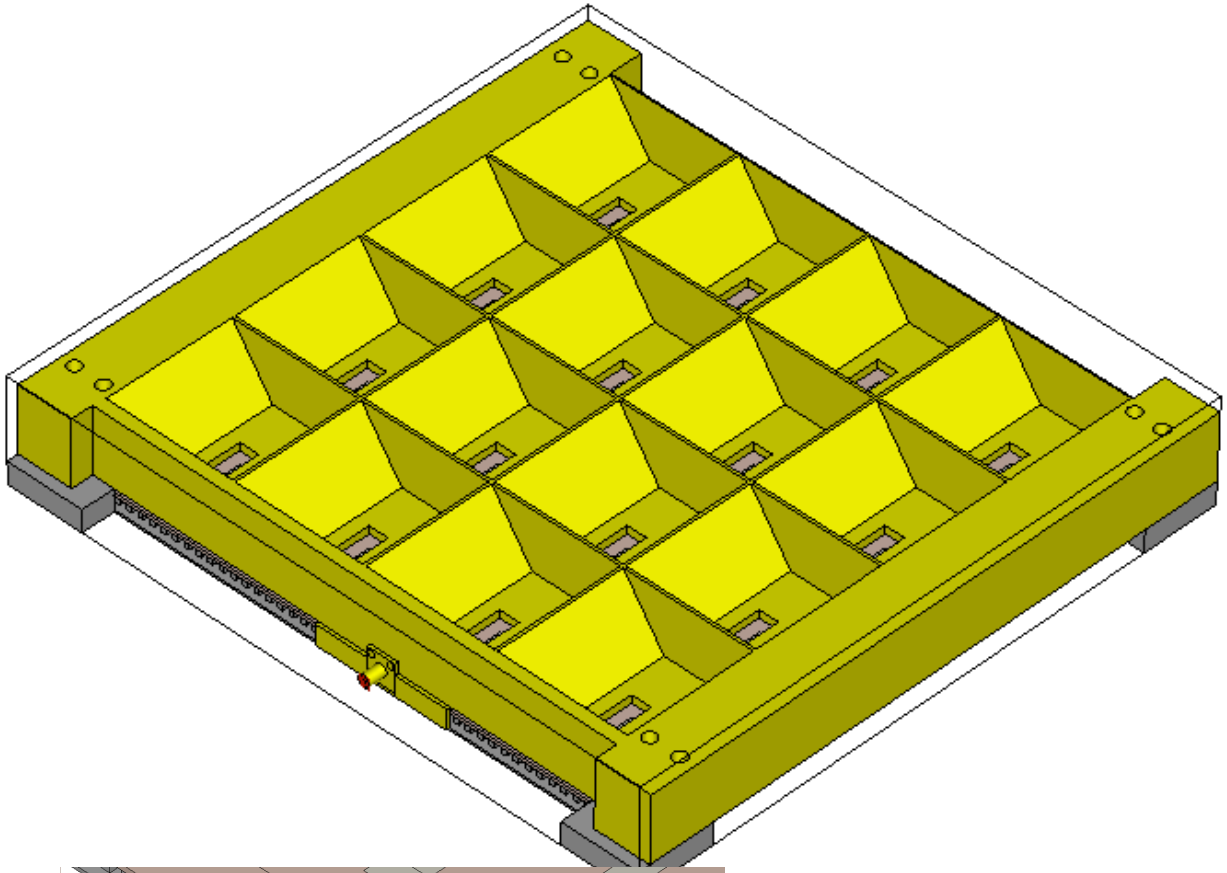


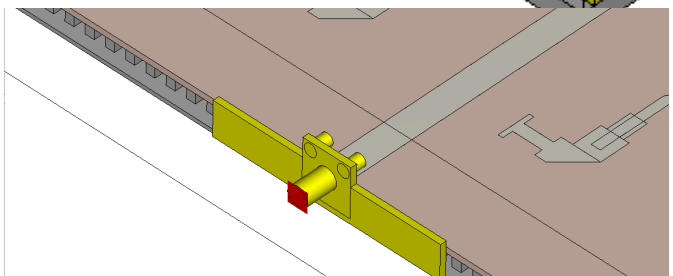
H-plane



E-plane

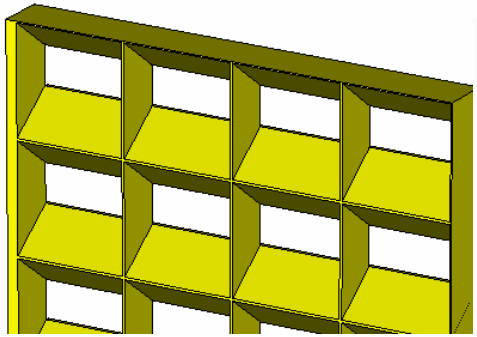
Inverted microstrip gap waveguide horn array at 10 GHz [58]



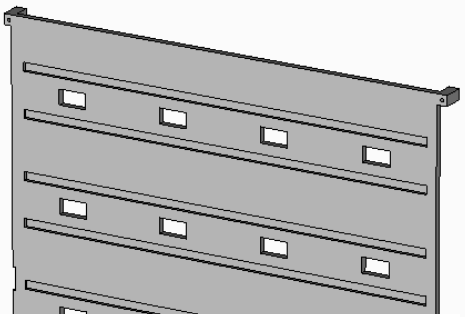


Inverted microstrip gap waveguide horn array at 10 GHz

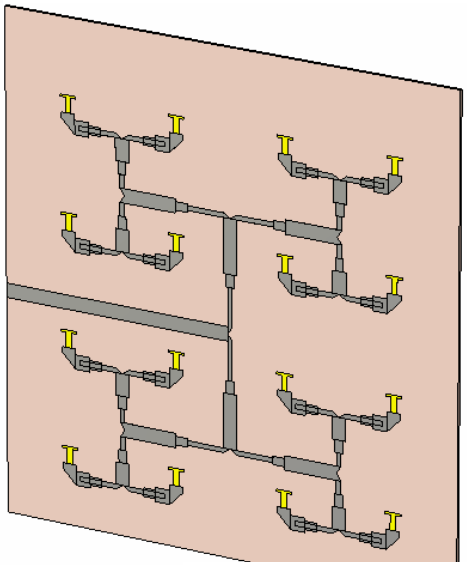
1. A plate of horns with metal rims
In the back (shown in 2.)
to connect to the slots plate



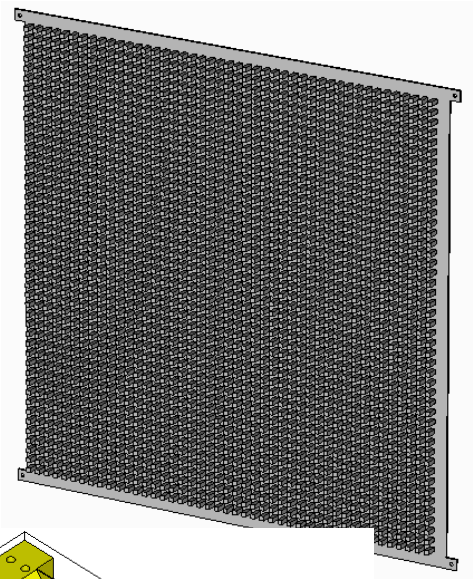
3. A plate of slots with holes
To connect the rims in 2.

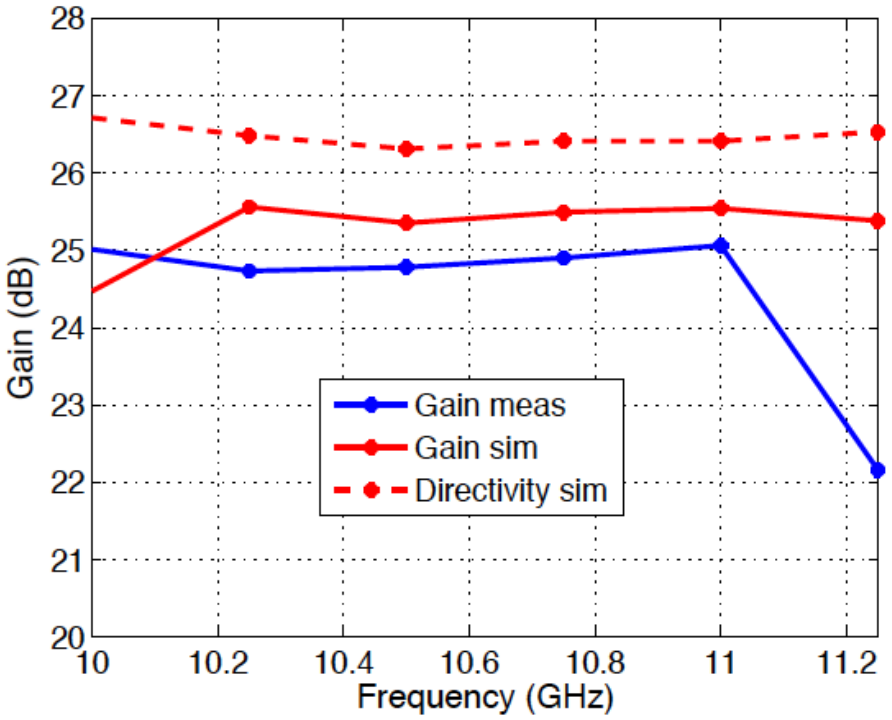


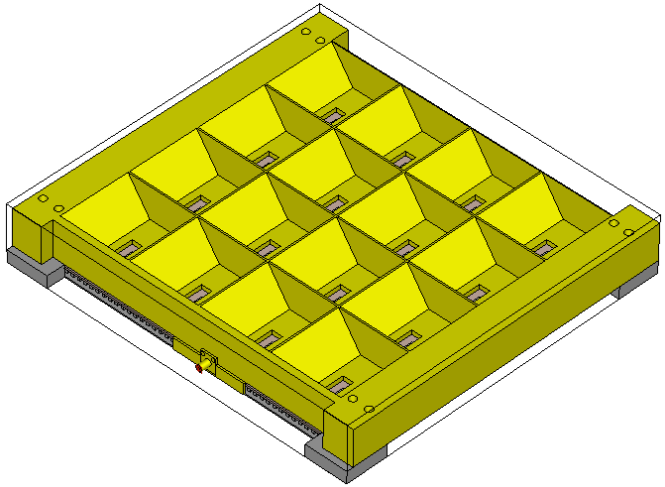
4. A plate of PCB.



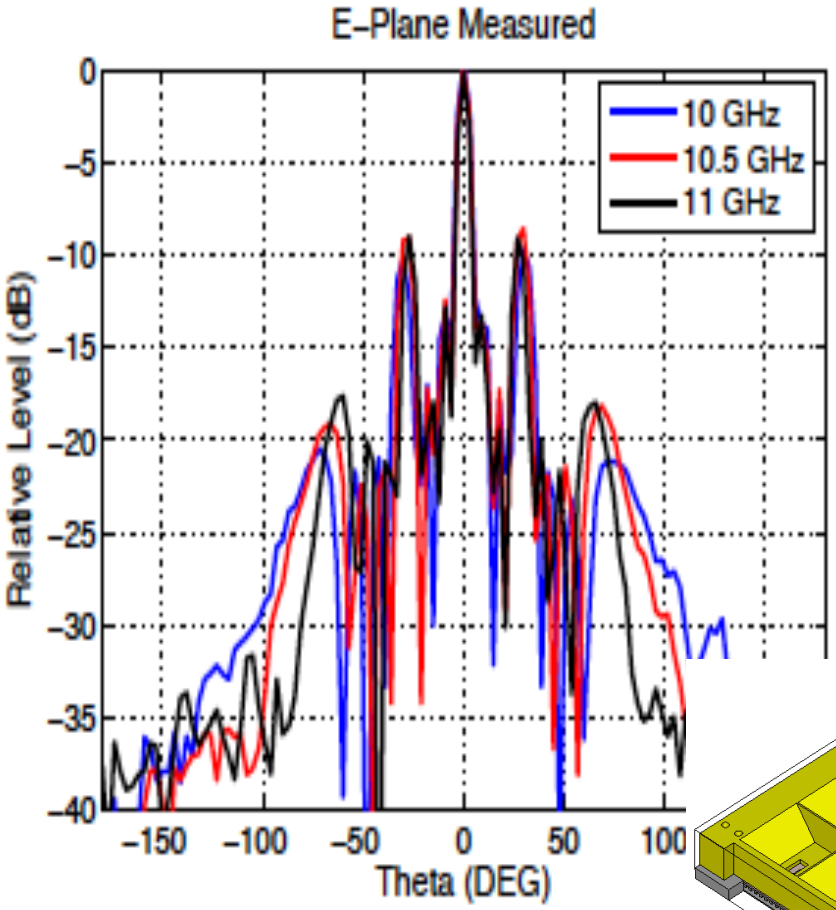
5. Lid of pins

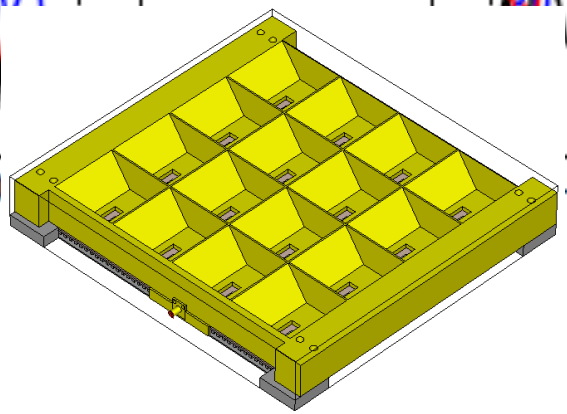


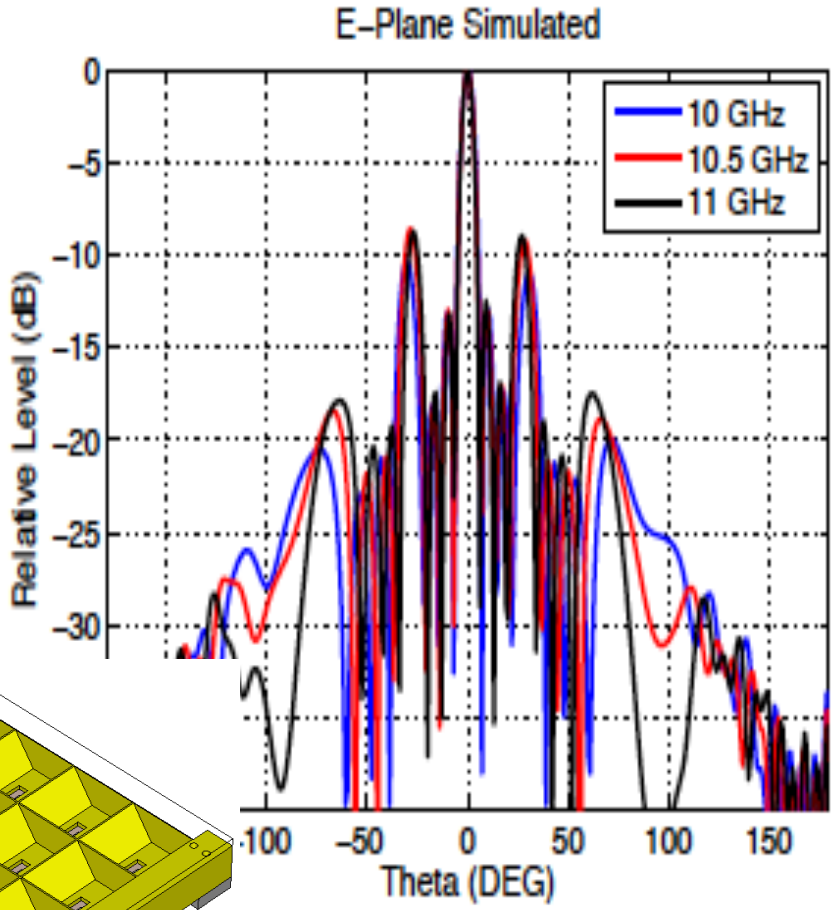




Typical measured and simulated radiation patterns 10-11 GHz [58]







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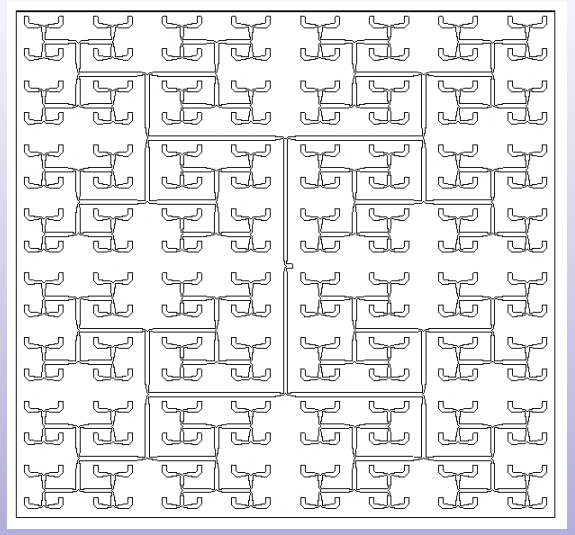
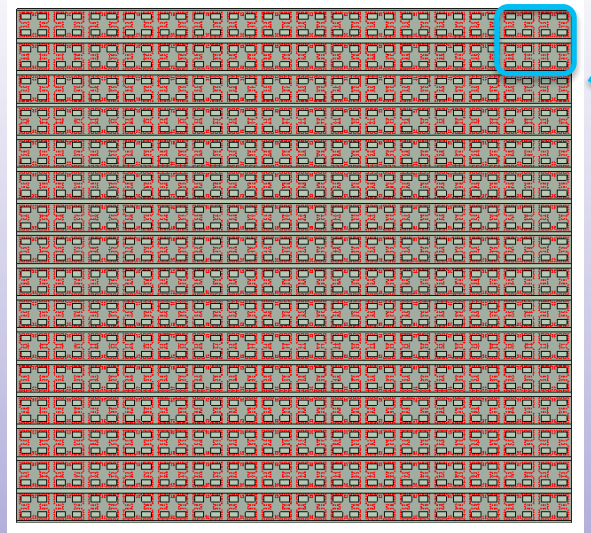
Directive 32x32 Slot Array for 60 GHz link

- Slot arrays for radar and communication applications
- High efficiencies at millimeter waves using hollow waveguide corporate distribution networks, but expensive.
- **Proposal:** 60 GHz slot array antenna using PCB technology

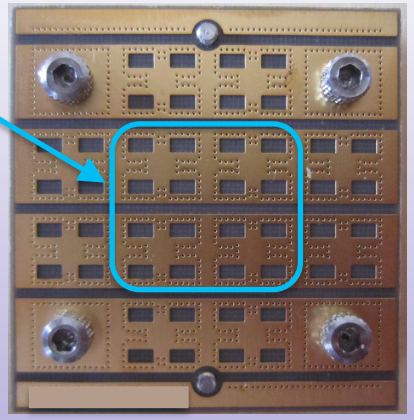
Corporate distribution network



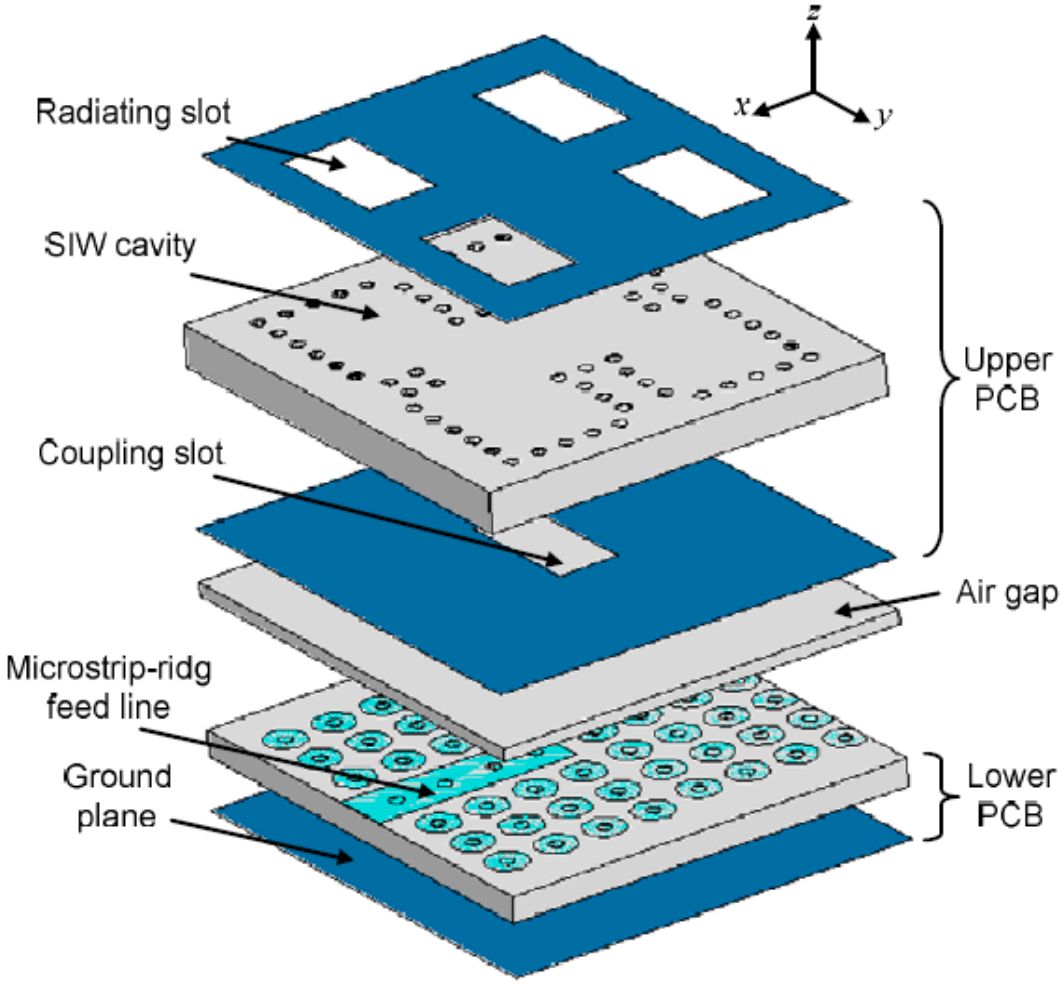
32 x 32 slot array



4 x 4 slot array prototype



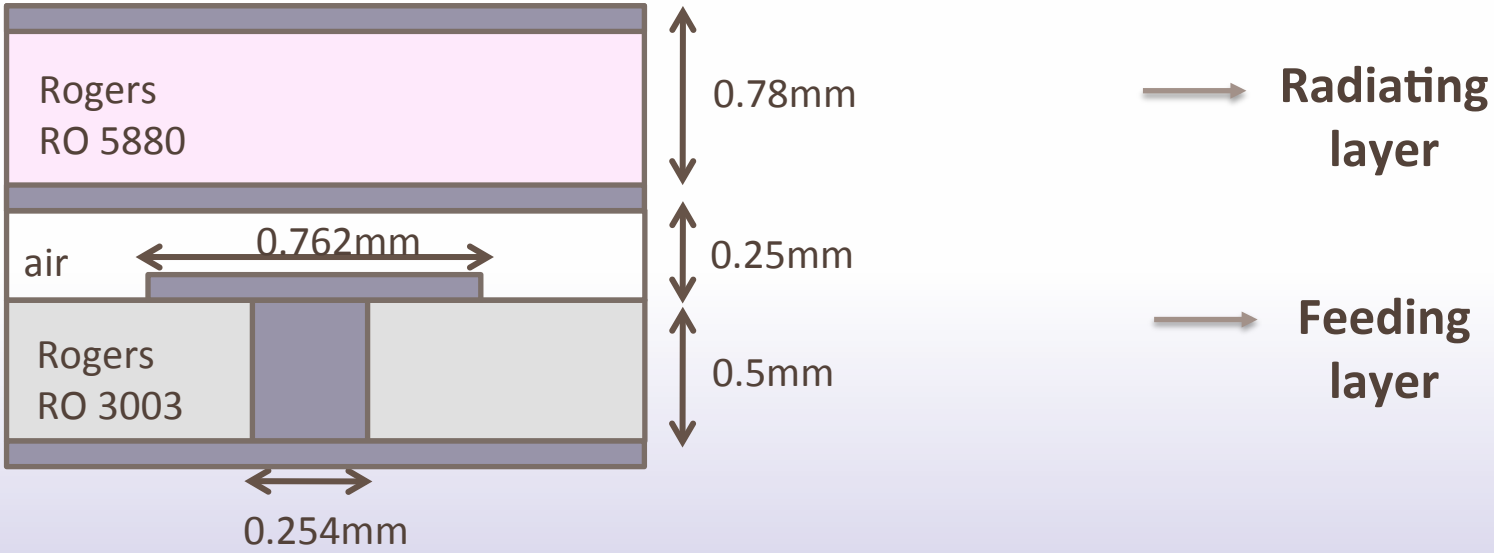
Multilayer geometry of unit cell of 32x32 slot array at 60 GHz [59]



- 2x2-slot element
- 57 GHz – 66 GHz (15% bandwidth)
- **2 PCBs**
- **SIW** and **microstrip-ridge gap waveguide**
- Low-loss corporate distribution network

Cross-section of Microstrip-Ridge gap waveguide

- Section view

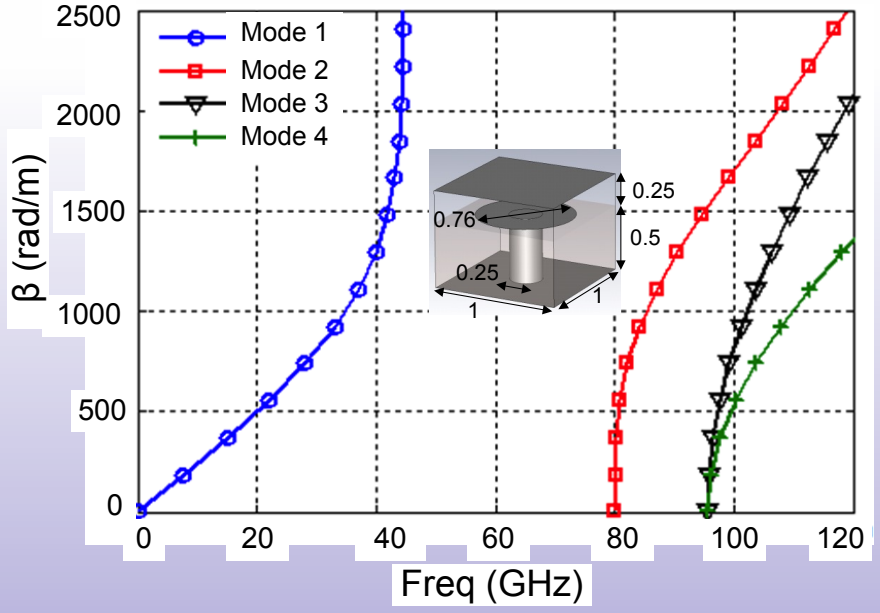


Vias period: 1mm

Stopband created by metallized via-holes

- **Feeding layer:** Microstrip-ridge gap waveguide corporate distribution network

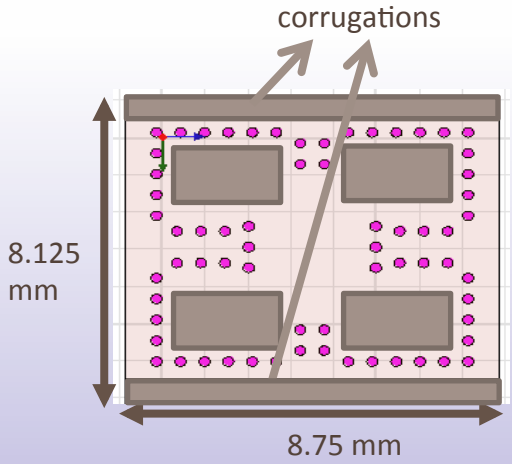
Parallel-plate stopband (44.5 GHz – 80 GHz)



Design principles of directive 60 GHz slot array [59]

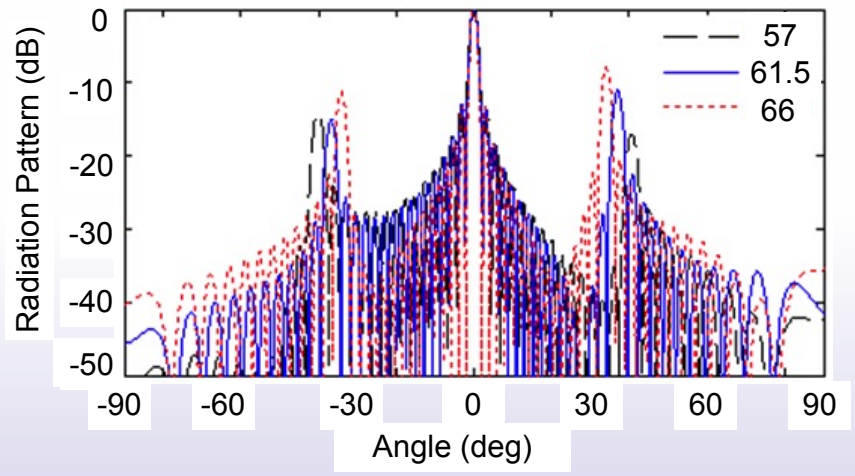
- The **design of the element** (2x2-slot subarray) was done in **infinite array environment**, and in terms of:
  - **return loss**
  - **power lost in grating lobes**

- **Smaller element spacing in E-plane**:
  - to avoid grating lobes
- **SIW corrugations in E-plane**:
  - to reduce mutual coupling
  - for better matching and grating lobe level

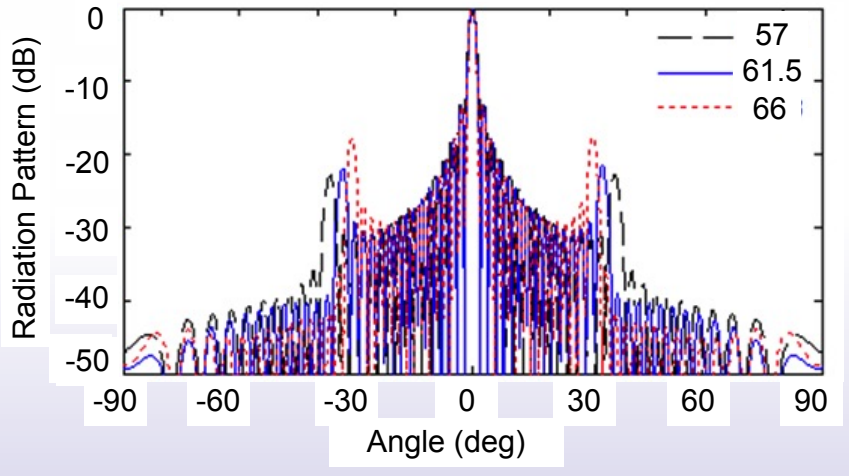


Simulation results [59]

- **Radiation patterns** of designed element with **32x32-slot array** aperture



E-plane



H-plane

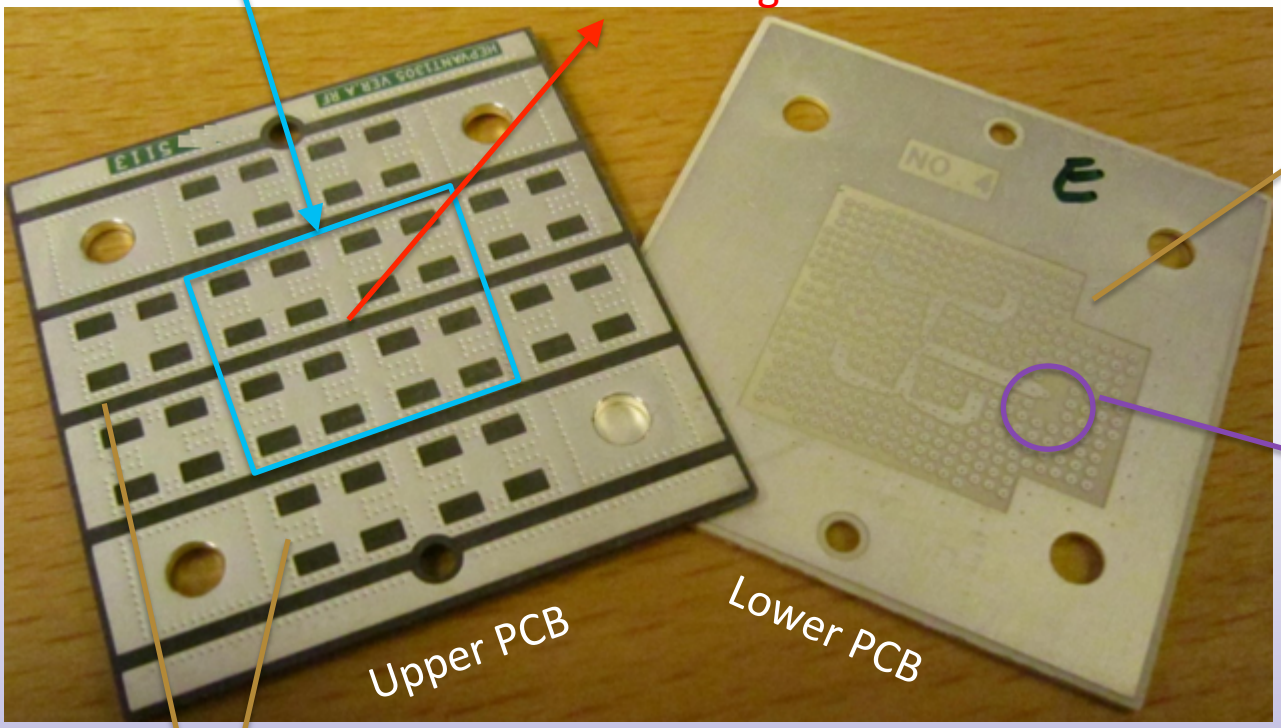
Simulated results [59]

- **Radiation characteristics** of designed element with **32x32-slot array** aperture

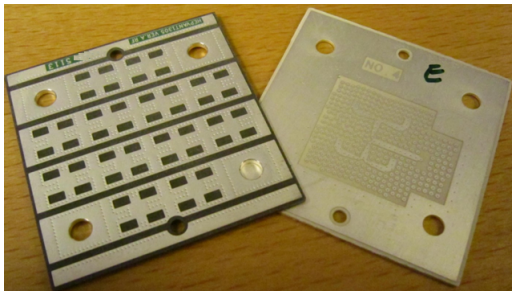
Frequency	**57 GHz**	**61.5 GHz**	**66 GHz**
Directivity (dBi)	38.62 dBi	38.82 dBi	38.64 dBi
Aperture efficiency (dB)	-0.54 dB	-1.00 dB	-1.77 dB
Grating lobe efficiency (dB)	-0.36 dBi	-0.61 dBi	-1.21 dBi
E-plane First grating lobe level (dB)	-14.25 dB	-11.06 dB	-8.00 dB
H-plane First grating lobe level (dB)	-22.94 dB	-22.00 dB	-17.83 dB

Validation

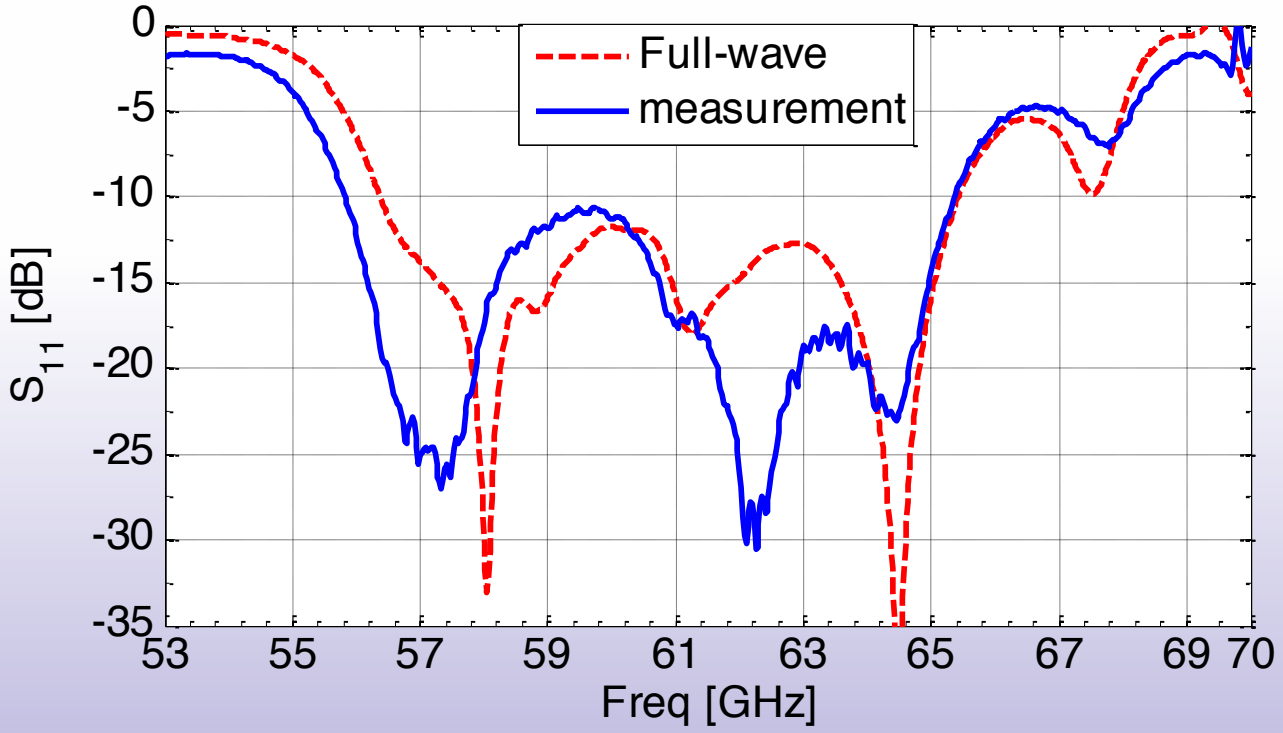
- **Small 4x4 slot array** (2x2 array of 2x2-slot subarrays)



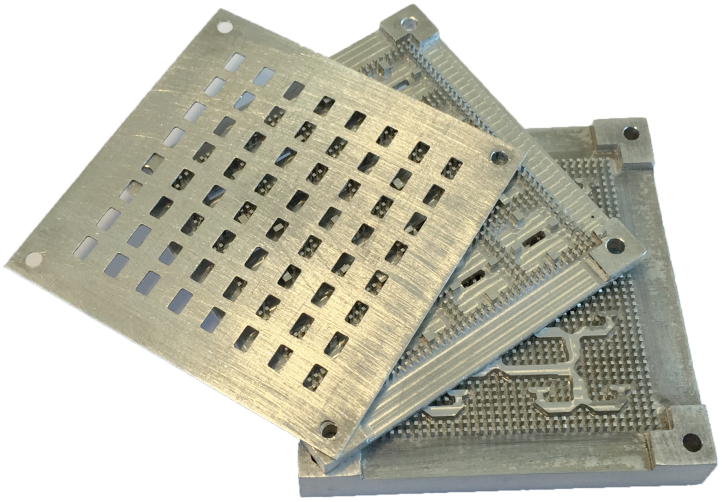
Validation [59]

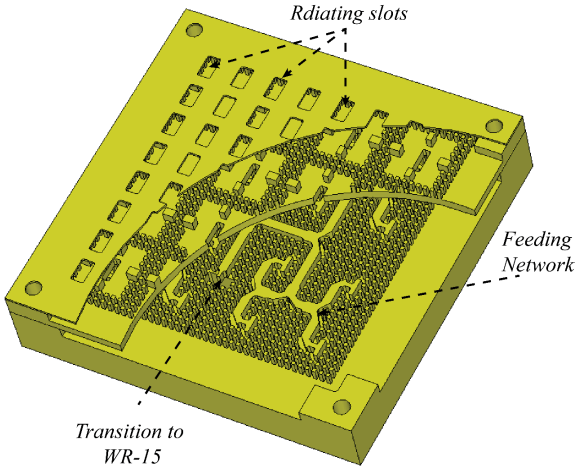


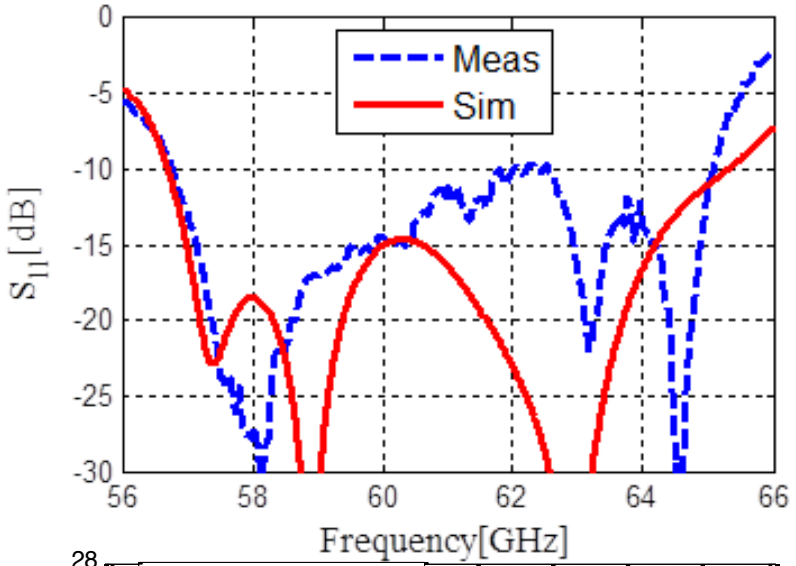
- **Reflection coefficient** of small 4x4 slot array

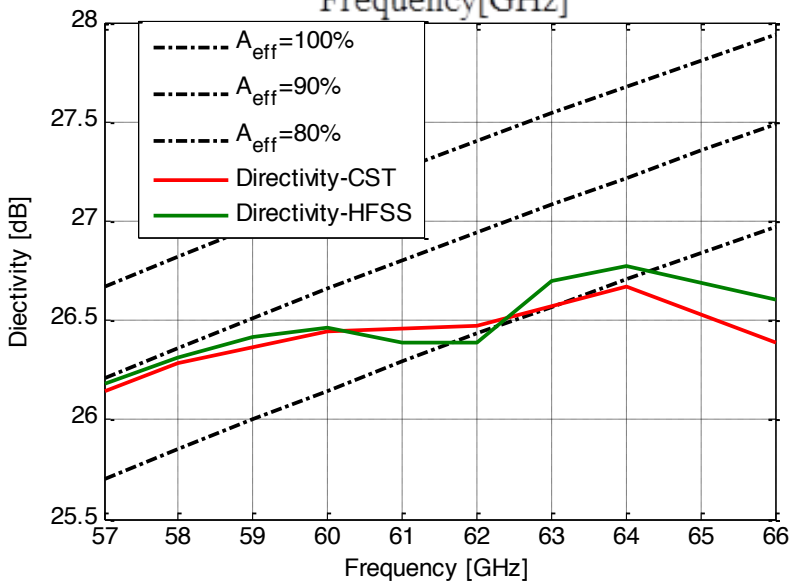


Here is an all-metal solution: Groove gap waveguide cavity and ridge gap waveguide distribution layer [60]

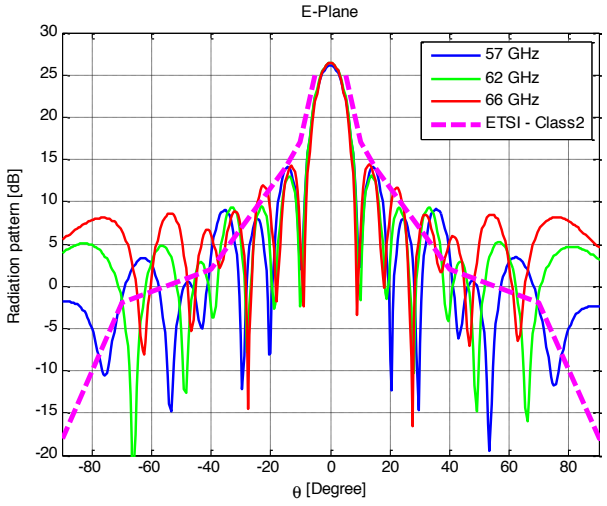


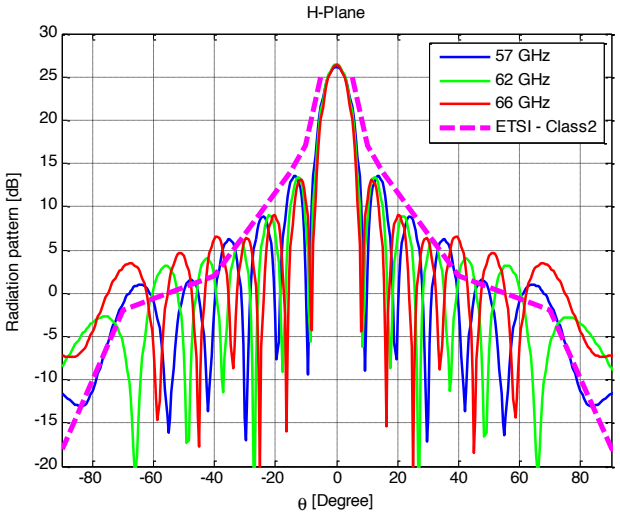


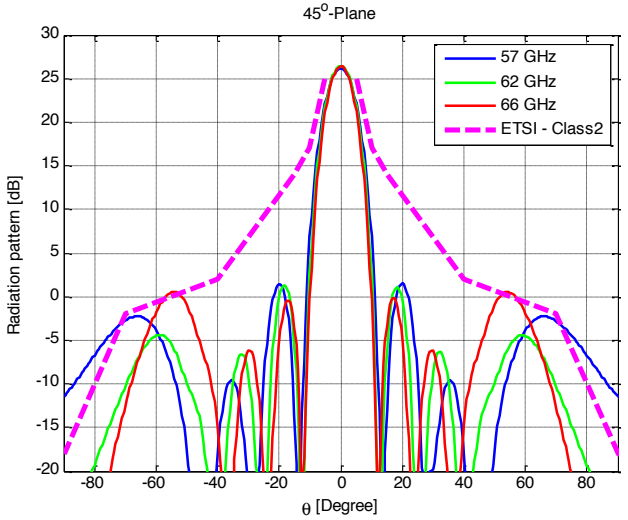


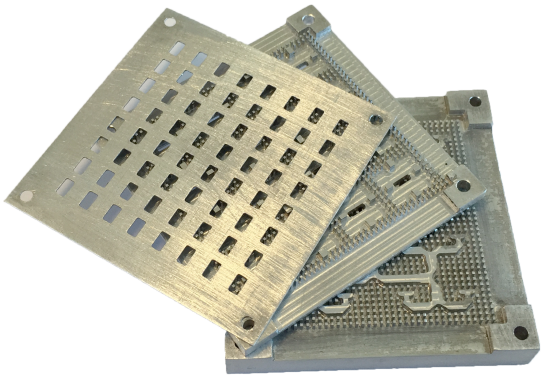


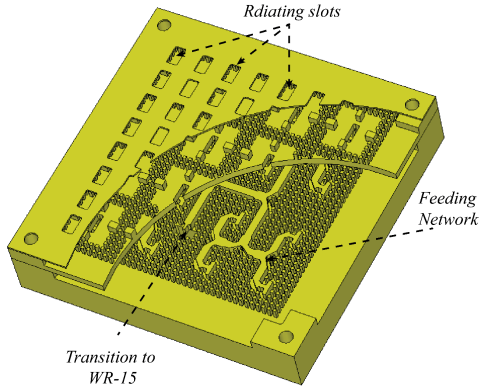
Measured radiation patterns of three layer all-metal gap waveguide antenna





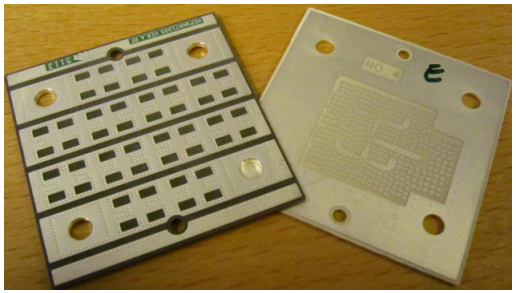


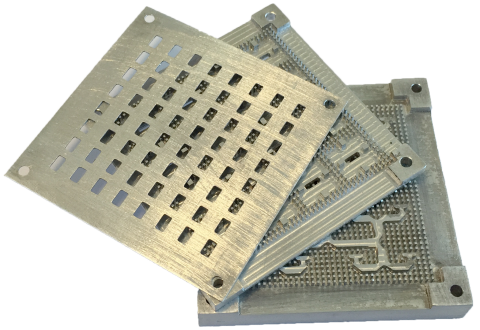




Conclusion for 60 GHz gap waveguide array

- Two 60 GHz wideband planar slot arrays with high efficiency have been designed, manufactured and measured.
- One is made in printed technology, combining gap waveguide and printed microstrip-ridge gap waveguide technology. This had larger losses than expected, and tolerance problems.
- The other is made by three milled metal plates using in groove gap cavity and ridge gap waveguides. Measured and simulated results are in quite good agreement.
- In mass production the all-metal solution must be manufactured by molding, die-casting, EDM die-sinking or etching.





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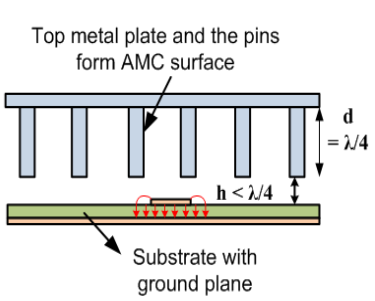
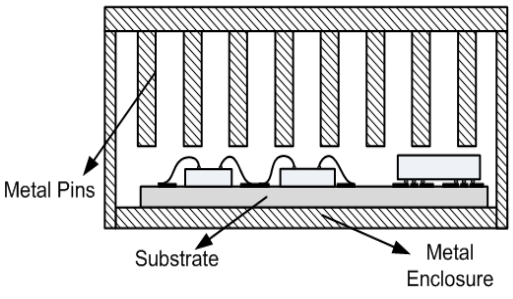
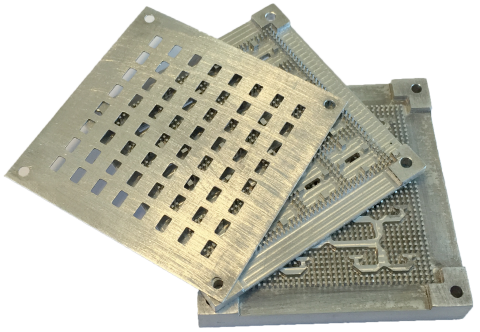
  Metamaterial-based horn-antennas based on soft and hard surfaces

Summary and Future

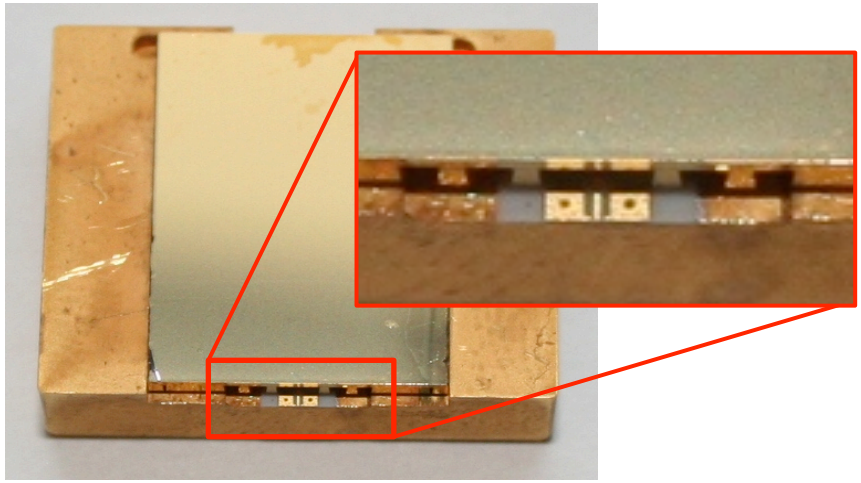
- The ideal soft and hard surfaces are PEC/PMC strip grids. These grids can today be used as canonical surfaces for intial creative designs in the same way as PEC and PMC surfaces.
- The canonical surfaces have already shown to be very useful.
- Unfortunately, PMCs and PEC/PMC strip grids of arbitrary and finite shapes are not included in all commercial electromagnetic softwares.
- Corrugations are the simplest and best realization of the soft surfaces.
- Pin surfaces are the simplest and best realization of the PMC in gap waveguides, but many other ways exist.
- The gap waveguide is a result of controlling wave propagation inside a narrow gap between a PEC and PMC surface, by using the cut-off property of this gap, and adding conducting elements such as grooves, ridges or strips in the PMC, along which the waves propagate.
- Gap waveguides are a result of early research on soft and hard surfaces
- Groove gap waveguides have similar electrical performance as rectangular waveguides, but they are planar in nature.
- PMCs (pin lids) can be used for electronic packaging, based on the gap waveguide concept. PMC packaging is also a numerical procedure making initial simulations much faster.
- Directive gap waveguides antennas have been realized and measured with good performance at 60 GHz.
- Gap waveguides are a potential THz technology, and some demonstrator circuits have been made, see next slide.
- The final commercial success of the gap waveguides depend on how affordable they are to mass produce compared to other technologies. Milling is too expensive for frequencies above 30 GHz.

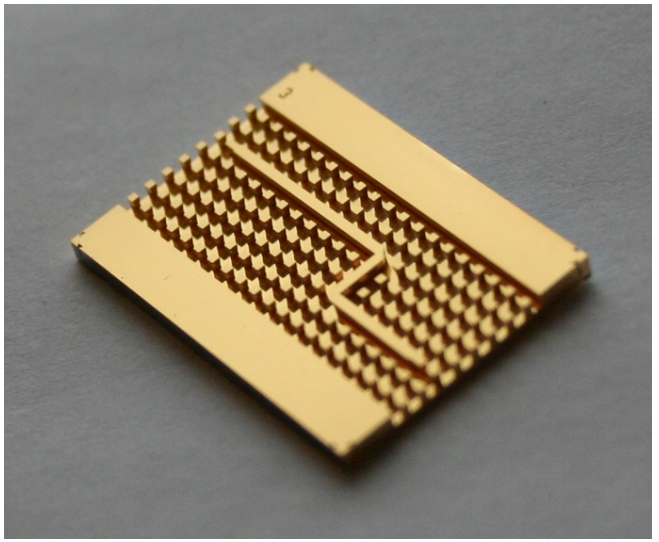


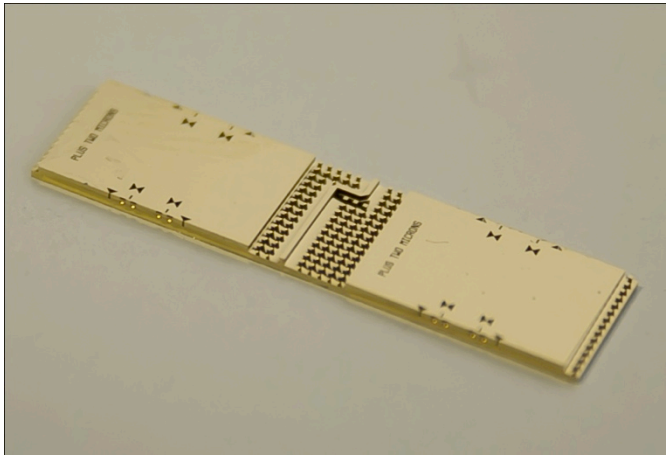


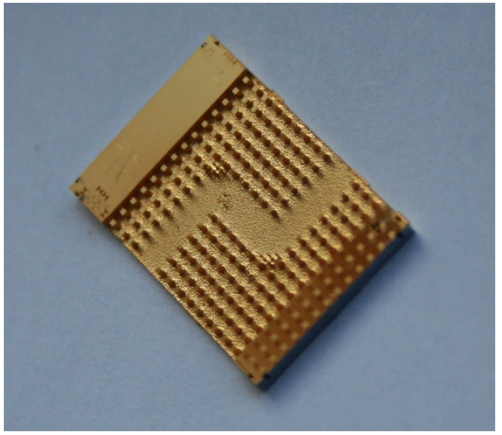


Gap waveguide demonstrators at 120 and 260 GHz manufactured by micromachining [65-66]









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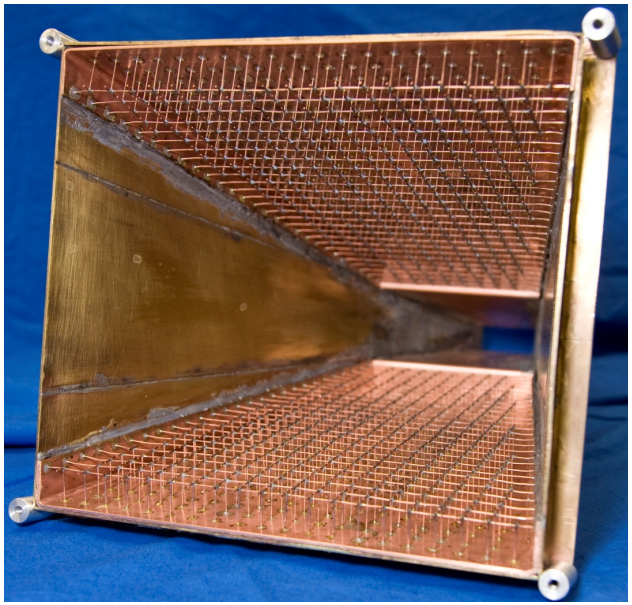
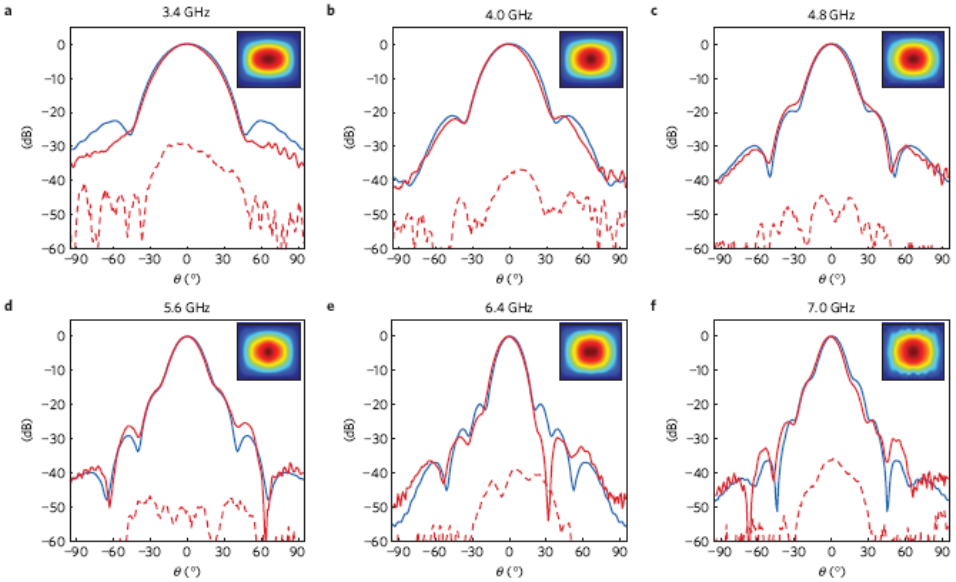
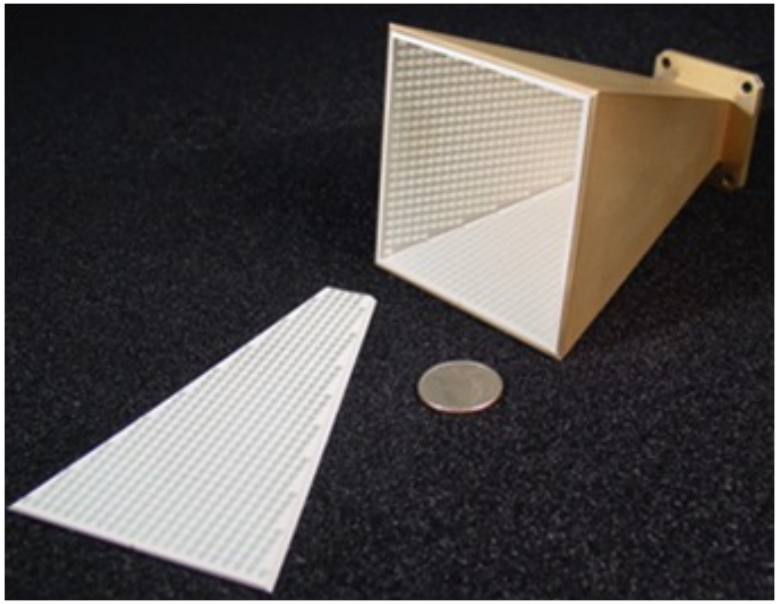
Erik Lier has the same soft/hard surface background as myself and has the last years been initiating meta-horn antenna works at Pennsylvania State University [6,37].

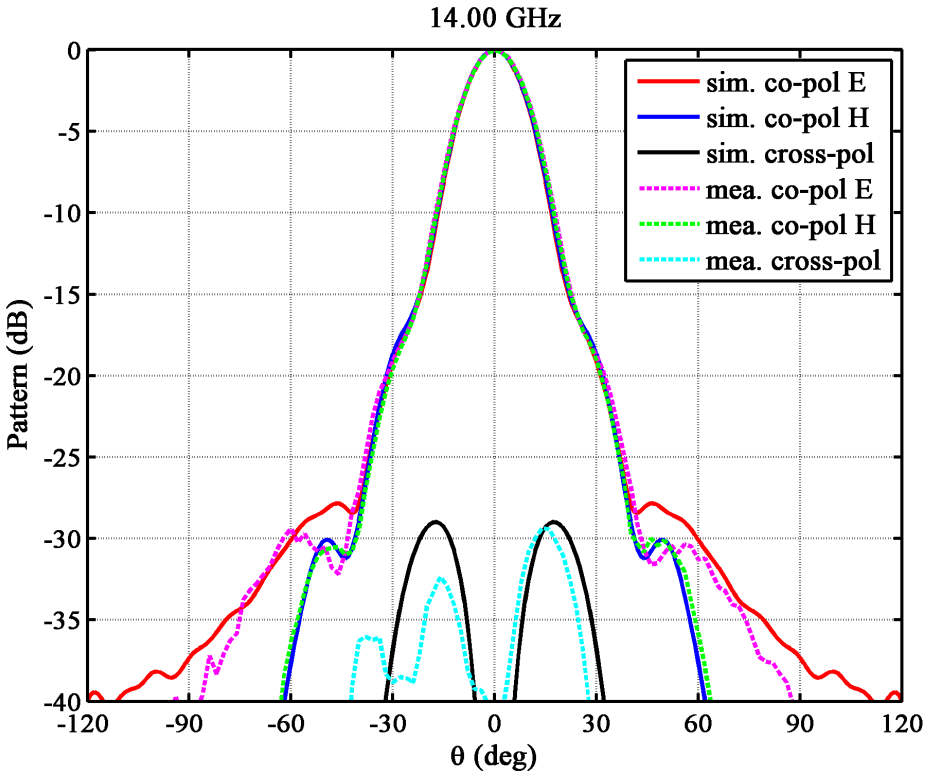




Linearly polarized soft horn made by a wire-type metasurface surface.

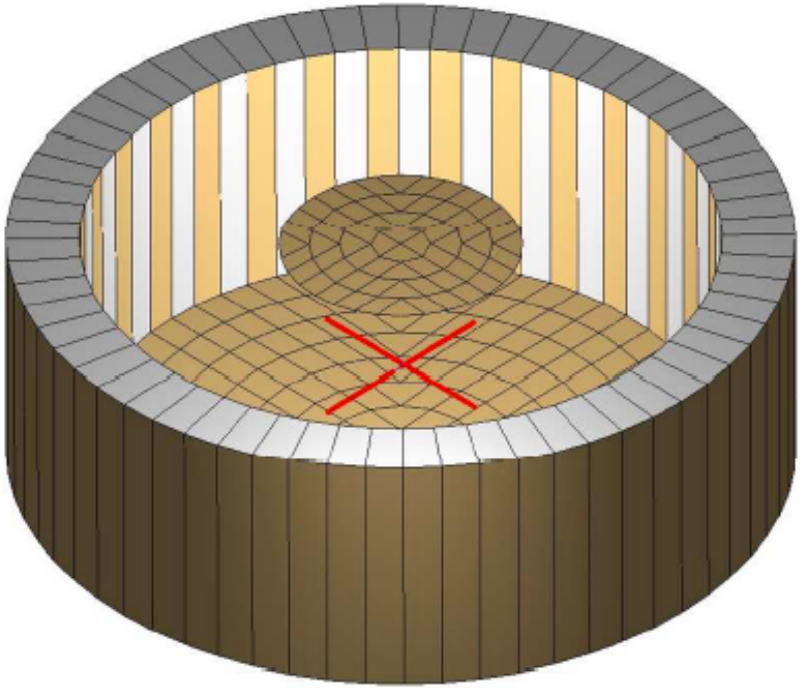
Printed meta-horn by Erik Lier at. al. [36]

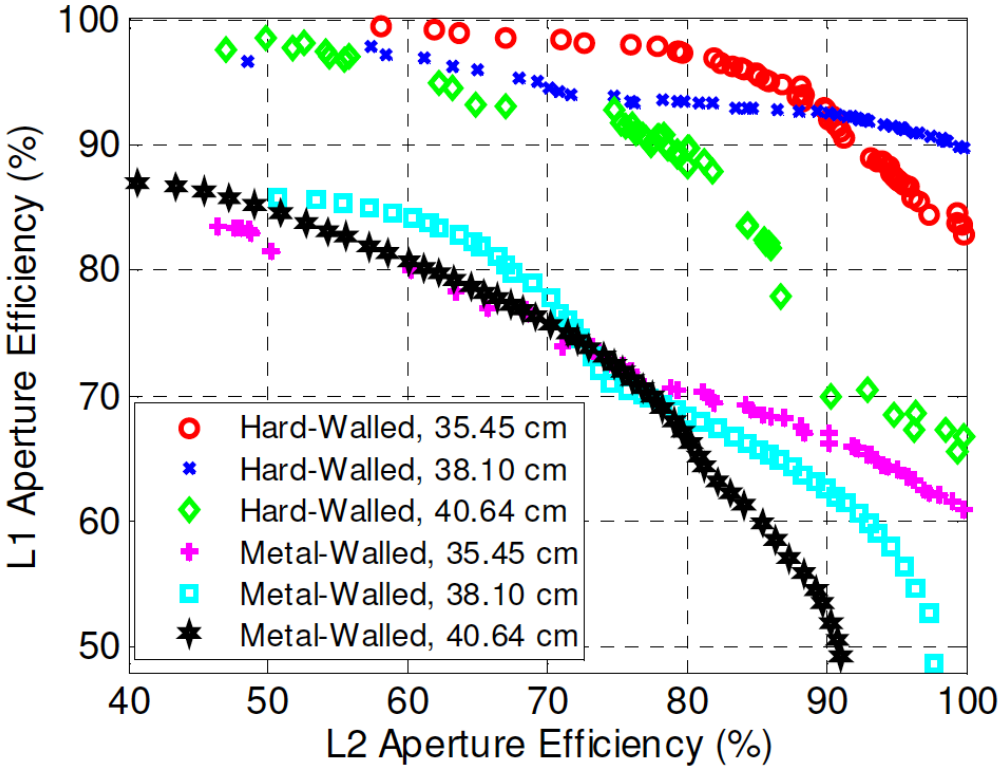




Dual-polarized soft horn made by printed metamaterial lining.

A hard-walled short backfire antenna with very high aperture efficiency (E. Lier 2015 [38])





Selected references by topic

Concept and overviews:

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